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Prepared for the

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13. ABSTRACT

The problem of flash blindness and chorioretinal burns resulting from exposure to the intense energy pulse from a nuclear fireball has been recognized as a potential threat to certain military and civilian population groups. The threat extends for many miles beyond the range where other immediate nuclear effects may be encountered. A considerable amount of research has been done to determine the thresholds for ocular effects and to develop countermeasures. However, additional efforts are required to assess the operational significance of visual impairment and to develop devices which will provide effective protection for larger population segments. Therefore, a need exists to disseminate critical information to various research and planning agencies.

A comprehensive, unclassified review of this problem was prepared, including information from classified weapons test reports. This review includes data on energy production, transmission, and absorption, ocular effects, countermeasure devices, and the variables used to make operational assessments of visual impairment.

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I. INTRODUCTION

Flash blindness and chorioretinal burns are forms of visual impairment resulting from absorption of excessive amounts of light and thermal energy on the retina. Flash blindness is a very common phenomenon, one that is often experienced on the highway, in the photographer's studio, in the welding shop, skiing, flying over water, etc. Permanent retinal lesions produce scotomas, or blind spots, and may be caused by direct viewing of high intensity light sources such as the sun (or a highly reflected image). Although retinal burns occur far less frequently than flash blindness, there are reports each year in the ophthalmology literature about solar burns. Reports of ocular effects from diverse incandescent or fluorescent sources such as blast furnaces, search lights, photo flash systems, electrical arcs, explosive flash devices, and more recently, lasers, appear from time to time in technical literature from a variety of fields.

The advent of the atomic bomb, while it cannot be credited for having introduced the problem, did serve to extend this visual hazard from the realm of clinical curiosity to a significant threat to large groups of individuals.

Apparently the extreme brilliance and possible visual hazard of the fireball was anticipated before the first atomic tests were conducted since observers' accounts of these tests make note of their having worn very dense lenses.

In 1951, the Air Force School of Aviation Medicine had a formal task, Project 4.3, "Flash Blindness" to test the effect of a nuclear detonation on the eye. These tests were conducted during Operation Buster in order to assess the day time flash blindness handicap and evaluate the effectiveness of certain eye protection systems. The data obtained in these tests indicated that flash blindness was not a significant handicap "during exposure to atomic detonation during day light operations at the distance from the detonation which would be safe from the standpoint of other hazards" (Ref. 10, page 249).

In the 1952 Tumbler-Snapper Test Series, information was collected on atmospheric transmission; this data was helpful in predicting retinal burn distances. However, it was not until the 1953 Upshot-Knothole Series that both the burn and flash threat were recognized as extending to ranges well beyond those of other effects. During these tests, research was conducted to determine what the effect of the dilated dark adapted pupil was on increasing the probability and severity of impairment. At that time, the Air Force School of Aviation Medicine was concerned about visual effects during night-time operations. It was concluded that a nominal yield bomb could produce chorioretinal burns in humans at distances out to 40 miles.

In 1953, Buettner and Rose, using unclassified data, published a report in the open literature predicting the optical phenomenon whereby eye effects may occur at extremely long ranges.

Retinal burns were investigated again in Operation Redwing (1956). "The significant conclusion of this test was that retinal burns were produced at distances greatly exceeding the limits for any other prompt and significant biologic effect of nuclear detonations" (Ref. 10, page 250). It was also recognized that the burn problem will increase in significance as the detonation altitude is increased.

In 1955, Rose, Brown, Byrnes, and Cibis (159) had published a clinical report of six cases of chorioretinal burns accidentally received during weapons tests.

Shot Teak (Operation Hardtack--1958) detonated at an altitude of 252,000 feet produced chorioretinal burns in test animals in an aircraft at 15,000 feet at a slant range of 307 nautical miles (153). It was concluded that minimal lesions could be produced in rabbits on the "surface at distances closely approaching 300 nautical miles from relative ground zero from a megaton detonation at excess of 200,000 feet altitude" (Ref. 10, page 250).

The production of retinal burns in the laboratory was initially developed as a clinical technique for treatment of retinal detachment, but was soon adopted for research on damage thresholds and weapons effects prediction. One of the earliest reports on laboratory burn thresholds for evaluating retinal hazards from weapons was published by Ham, Wiesinger, Schmidt, et al.in 1958 (86). This work has since been extended by Geeraets and Ham to include shorter pulse durations (74).

Laboratory studies of flash blindness and chorioretinal burns have been (and currently are) directed at the problems of determining thresholds, description of effects and recovery, and manipulation of pulse characteristics to determine mechanisms of damage.

Flash blindness research was a natural extension of the early dark adaptation studies. In 1938, Crawford (41) was doing theoretical work and apparatus development for production of sudden flashes in vision research. In 1947, he used the term flash blindness with reference to visual recovery times from gun flashes. Green (80) was using photo flash bulbs and reflecting surfaces to produce flash blindness in 1950, and in 1952, Whiteside (191) published a complete study on his flash blindness research. Metcalf and Horn, in 1958, published a report on visual recovery from high intensity sources.

It is interesting to note that the development work on eye protective systems preceded the detailed research on flash blindness and chorioretinal burns. When sufficient information on the seriousness of the threat became available from the nuclear weapon tests, military agencies were quick to support research on eye protective systems. Extensive laboratory studies of visual effects were not initiated until the late 1950's. However, since that time, research on transient and permanent impairment and in protective systems has been very active.

The Defense Atomic Support Agency (DASA) now has the responsibility for making data on nuclear weapons effects available to military and civilian defense agencies in order that the various nuclear threats may be assessed and counteracted, where possible. As a part of this responsibility, work was initiated by DASA to compile current information on flash blindness and chorioretinal burns into a comprehensive, unclassified report. Sources for background information were classified weapons test data, the open literature, and personal interviews with authorities in the field.

There are well over two hundred reports and papers dealing directly or indirectly with the visual effects resulting from exposure of the eye to the intense light and thermal energy pulse of a nuclear fireball, and on countermeasure development. Many of these papers include a statement about the threat that photostress imposes upon vision and upon performance of critical visual tasks during mission performance. So, rather than prepare one more introduction to the subject, the opening paragraph of the DASA work statement to Bio-Dynamics, Inc. is quoted as being a concise definition of the problem and of the contract objectives.

"The problem of flash blindness and retinal burns (received) during the detonation of atomic weapons has long been recognized as a severe hazard. This hazard is a potential threat to many segments of civilian and military populations, i.e., atomic support troops, aircraft pilots, anti-aircraft and anti-missile installations, and exposed civilian personnel within extensive slant ranges of air-burst weapons. Thus, there is a prime requirement to disseminate, to appropriate research and defense agencies, current and known facts about weapon-produced ocular injury. This information should include not only phenomenology, and effects, but protection, treatment, and prediction methods as well".

Prior to the initiation of this contract, DASA had compiled a classified working report (38) covering photostress studies and countermeasure evaluations conducted during nuclear weapon tests. In addition to the bibliography of the DASA report, we have added references from the open literature on flash and burn research, new developments in countermeasure devices, and where possible, interpretations of the research.

A number of the documents on chorioretinal burns and flash blindness which were reviewed were difficult to interpret critically. Some of the problems encountered are cited in the technical sections of the review. Typical difficulties involved inadequate description of terminology, mixed terminology and units, gross errors in calculation, misinterpretations of research findings, and conclusions based on insufficient evidence. In many cases, it was necessary to repeat calculations and make conversions of units in order to interpret and compare findings. For example, in the section on flash blindness, data from many reports had to be laboriously converted to common units. These converted data are presented in tables for the readers' convenience.

II. OPTICS AND THE EYE

A. Introduction

Chorioretinal burns may be produced in man or animals under certain conditions at distances of hundreds of miles from a high altitude nuclear detonation. At such distances the thermal dose incident upon the skin or cornea is not sufficient to produce damage to these surfaces. However, because of the focusing effects of the eye the thermal dose incident on the image formed on the retina may be as much as several thousand times greater than the corneal dose. Mathematical relations useful in determining image size and thermal concentration are described in the following paragraphs.

B. Image Formation

The velocity of light may differ significantly in various media. Because of this property, light rays can be refracted (bent) when passing from one medium to another, the relative refractive effects depending on the ratio of the velocities and on the curvature of the interface. Optical systems, such as a camera or the eye, utilize refractive effects to bring light rays to a focus on a photosensitive surface. When properly focused, a sharp image of the light source is formed; i.e., all light rays coming from a point on the source, and which penetrate the camera lens or eye, converge at a corresponding point on the image. The distance between the optical center (nodal point) of the lens and the surface on which the image will be focused depends on the distance of the source from the optical center and on the refractive power of the lens.

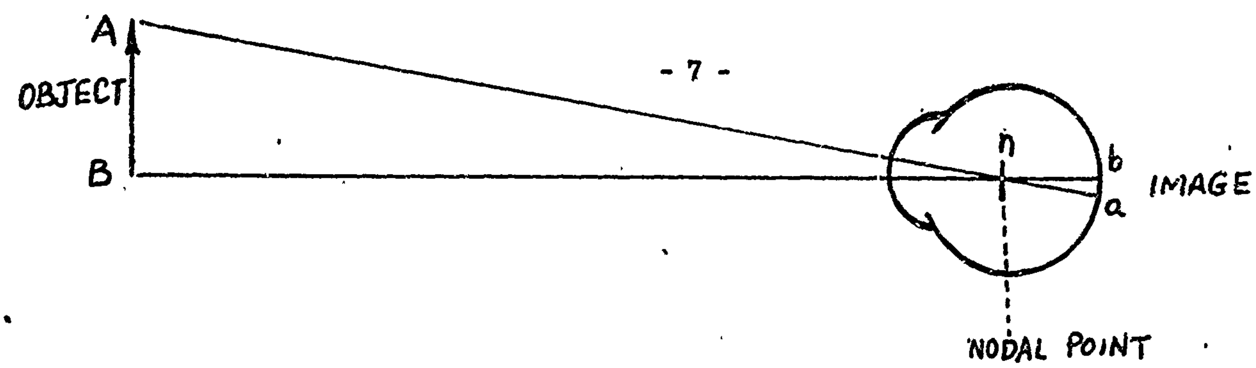

Figure 1

The reduced eye, showing the relationship between the length of an object, AB, and the image, ab.

In a camera, the lens has a fixed refractive power and must be moved closer or further from the image plane to focus objects at differing distances. In the eye, the distance between lens and retina is fixed, so that the refractive power of the lens must be changed to focus objects at differing distances.

In the eye, light is refracted at the anterior surface of the cornea, at the anterior surface of the lens, and at the posterior surface of the lens. It is cumbersome to trace the path of light rays through multiple refractions, and for general discussion, it is convenient to consider all refraction to occur at a single interface. Listing's "reduced eye" (Figure 1) is used as a model for this simplification. The two triangles ABn and abn are geometrically similar and therefore we can compute the image dimension (ab) if we know the object dimension (AB) and the distances of object and image from the nodal point:

$$\frac{\text{Image dimension}}{\text{Object dimension}} = \frac{\text{Distance of image from nodal point}}{\text{Distance of object from nodal point}}. \tag{1a}$$

The distance of the image from the nodal point (approximately equal to the focal length) is about 17 mm, and the distance from the anterior corneal surface to the nodal point is about 7 mm. For objects located at distances greater than several meters, the relation is approximately:

$$\frac{\text{Image dimension}}{\text{Object dimension}} = \frac{0.017 \text{ meters}}{\text{Distance to object (meters)}}. \tag{1b}$$

Thus, as range increases, the dimensions of the image decrease. The retinal area covered by an image therefore varies inversely with the square of the distance from the source. Since the energy flux also varies inversely with the square of the distance from the source, the energy per unit image area will be a constant at all distances, neglecting atmospheric attenuation. Simply stated, as distance from the source increases both the energy incident on the cornea and the retinal image area decrease at the same rate, thus maintaining a constant retinal irradiance.

C. Retinal Dose

All energy incident on the retinal image must pass through the pupil. When there is only one significant source of energy in the field of view, the total retinal energy will be concentrated on the image and can be computed as follows:

$$\text{Total retinal energy} = (\text{corneal energy/unit area}) \times (\text{pupil area}) \times T \tag{2a}$$

$$\text{Image energy/unit area} = (\text{total retinal energy/image area}) \tag{2b}$$

where T is the transmissivity of the pre-retinal ocular media. The transmissivity of the ocular media varies with age and with the wavelength of the incident radiation (see Chapter V). Different investigators have reported measurements which differ appreciably for certain portions of the visible and near infrared spectrum (13a, 72), although there is general agreement that transmission is negligible below 350 mμ and above 1400 mμ.

The image exposure is related to the product of the corneal exposure, the transmissivity of the ocular media, and the ratio of pupil area to image area:

$$\text{Image exposure} = \text{corneal exposure} \times T \times \frac{\text{pupil area}}{\text{image area}}. \tag{3}$$

The preceding equations are approximations which are valid for most conditions but invalid for extremes of image size. For example, by equation 1b, a true point source of light energy would produce an infinitely small image on the retina. If the point source produced a finite corneal exposure, the image exposure would approach an infinite value, according to equation 3. However, because of imperfections in the optics of the eye, light from a point source is spread over a considerable area. The energy intensity at the center of a point source image will be approximately equivalent to that computed when all of the energy passing through the pupil is considered to fall on an image with a radius of 10 microns. The intensity falls off rapidly with increasing distance from the image center, reaching a half value 4 microns from the center (121).

For purposes of retinal exposure computation, a source subtending a visual angle of 3 minutes or less, or a circular source located at a distance one thousand times or more greater than its diameter, may be regarded as a point source.

D. Computation Examples

1. High Altitude Detonation

Consider a detonation at an altitude of 100 km with a fireball 100 meters in diameter, as viewed from the ground directly below with a light adapted eye (pupil 2 mm in diameter), or a dark adapted eye (6 mm pupil). From equation 1b:

$$\frac{\text{Image diameter}}{100 \text{ meters}} = \frac{0.017 \text{ meters}}{10^5 \text{ meters}}$$

$$\text{Image diameter} = 0.017 \times 10^{-3} \text{ meters} = 17 \text{ microns.}$$

Since the intensity in the center of the image formed by a point source is only as great as would be produced if the energy were uniformly distributed over an image with a 20 micron diameter, it is apparent that imperfections in the eye will reduce the energy intensity on the image in this example (121). We should therefore use an equivalent diameter of at least 20 microns to compute the energy intensity in the center of the image. By equation 3:

on the retina. If the point source produced a finite corneal exposure, the image exposure would approach an infinite value, according to equation 3. However, because of imperfections in the optics of the eye, light from a point source is spread over a considerable area. The energy intensity at the center of a point source image will be approximately equivalent to that computed when all of the energy passing through the pupil is considered to fall on an image with a radius of 10 microns. The intensity falls off rapidly with increasing distance from the image center, reaching a half value 4 microns from the center (121).

For purposes of retinal exposure computation, a source subtending a visual angle of 3 minutes or less, or a circular source located at a distance one thousand times or more greater than its diameter, may be regarded as a point source.

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E. Summary

Simple equations have been presented which relate retinal image size to size and distance of the source. Using the equations developed in Section IV to compute fireball size, the retinal image size may be computed for any slant range. It is shown that retinal irradiance can be computed by multiplying the corneal irradiance (see Section IV) by the transmissivity of the ocular media and the ratio of pupil area to image area. Examples have been included.

III. ELECTROMAGNETIC RADIATION (EMR), PRODUCTION, TRANSMISSION, AND REFLECTION

A. Production of Electromagnetic Radiation (EMR)

1. Introduction

Those features of nuclear or thermonuclear detonations which are significant to the production of chorioretinal burns or flashblindness are discussed in this section. The electromagnetic radiation from nuclear weapons which produces temporary or permanent visual impairment constitutes a portion of the "thermal pulse". This description of thermal pulse characteristics has been abstracted primarily from Glasstone's The Effects of Nuclear Weapons (EMW) (78), supplemented by information from a number of other authors who have specifically treated the ocular hazard. The description will be restricted to those details necessary for the interpretation of chorioretinal burn experiments conducted on animals, tests of protective devices, flashblindness experiments, or accidental exposures of humans. The data include the amount and spectral distribution of thermal radiation received at a distance from the burst, size of the radiating fireball, and the time characteristics of the thermal pulse and fireball size. These variables depend, in turn, on weapon variables such as yield and burst environment (primarily altitude). Scattering, absorption, and reflection of the thermal radiation by environmental factors represent intervening variables and will be discussed in the succeeding section.

2. Fireball Development

At detonation about 70% of the fission (and fusion) energy appears as primary radiation. Subsequently, about half of this primary radiation may be converted into blast effects. In a nuclear explosion temperatures of tens of millions of degrees may be reached, and since the wavelengths of the emitted energy vary as the fourth power of temperature, most of the primary emission consists of x-rays. At sea level the x-rays are absorbed by the surrounding air, heating the air to incandescense to form a fireball. The visible and infrared radiation from the incandescent fireball produce the visual impairment hazard for observers.

For detonations about the earth's atmosphere, the thermal energy received at sea level consists of direct radiation from the expanding weapon debris together with secondary emission from the interaction of radiant energy with upper atmospheric constituents.

During the initial stage of low altitude fireball development, the mean free path of the radiation is large with respect to the dimensions of the gaseous volume. This is the "isothermal" stage during which the energy transfer from the hot interior to the cooler exterior of the fireball is rapid, and temperature gradients within the fireball are small. As the fireball expands, it continues to cool, causing the rate of expansion to decrease. In the meantime, the expanding debris of the weapon materials form a "hydrodynamic front" which acts on the ambient air like a fast moving piston, creating a spherically expanding compression or shock wave. Initially, the shock front expands less rapidly than the surface of the radiation fireball. As the radiation front cools, the mean free path of the radiation is reduced. Therefore, the rate of expansion slows. The shock front, which continues to expand at a high rate, then catches up with the radiation front. The phenomenon when the shock front moves ahead of the radiation front is called "hydrodynamic separation" and is of great significance to the chorioretinal burn and flashblindness problem. Although the compressed air in the shock front has been heated adiabatically to incandescense, it is still much cooler than the isothermal sphere. Due to the opacity of the shock front, the radiant thermal energy incident on a distant surface decreases after hydrodynamic separation (i.e., the "apparent" surface temperature of the fireball is less). However, the pressures in the shock wave are reduced as it expands, allowing the shock front to cool until it gradually loses its opacity. When the hotter interior of the fireball becomes visible through the shock front, "breakaway" has occurred, and thereafter the thermal energy incident on a distant surface increases rapidly as the apparent surface temperature of the fireball typically increases to about 7,700° C (apparent surface temperature during this phase may vary from about 3,000 to 8,000°).

The thermal energy incident on a distant surface thus occurs in two pulses, the apparent surface temperature passing through an initial maximum followed by a minimum and then by a second maximum. The time history of the development of these pulses is dependent on altitude of detonation and yield of the weapon. For a 20 KT weapon detonated at low altitude, hydrodynamic separation occurs after about one millisecond (0.001 second), at which time the fireball diameter is approximately 25 meters. The apparent surface temperature continues to fall until a minimum is reached at about 11 ms. Breakaway occurs approximately 15 ms after detonation when the fireball diameter is about 200 meters. The fireball continues to expand to a maximum diameter approximately twice that at breakaway, although the size is not well defined in the later stages. At very high altitudes, the air density is too low and the mean free path of the x-rays too long to produce conditions which cause the biphasic emission. The energy is then released in a single pulse which peaks sharply in a fraction of a millisecond. The peak is characterized by a very fast rise time to a high value, a sharp fall to a small fraction of the peak emission rate, and then a slow decay of the remainder.

3. Scaling of Effects with Yield

Yield and burst height influence the thermal radiation from a nuclear detonation. For low altitude air bursts, the total long range thermal energy (E_{total}) radiated averages about 33% of the yield (78):

$$E_{total}(\text{kilotons}) = 0.33\ W$$

$$E_{total}(\text{calories}) = 0.33 \times 10^{12}\ W$$

where W is the yield in equivalent kilotons of TNT. One kiloton of TNT is defined as 10^{12} calories of energy (78). The thermal energy percentage may differ slightly for extremely small or large bursts, is less for surface bursts, and larger for high altitude bursts (see Part 4).

The time to reach various stages of fireball development varies with yield and burst altitude. For atmospheric bursts, the times may be approximately determined by the following square root relations (78):

Time to thermal minimum (t_{min}) between the two pulses (seconds)

$$t_{min} = 25 \times 10^{-4} W^{0.5}$$

Time to maximum (t_{max}) of the second pulse (seconds) = $32 \times 10^{-3} W^{0.5}$. Hillendahl (94a) presents scaling equations with a slightly smaller exponent, including the following formula for computing time to the first peak:

$$\text{Time to first peak (seconds)} = 10^{-4} W^{0.42}$$

Solution of the above equations may be obtained from Figure 2. These values may be significantly in error when applied to fractional KT or tens of megaton (MT) yield weapons. Thus, it may be desirable to use 0.42 as the exponent of yield and increase the constant about 30%.

Fireball size varies at any phase with yield and altitude. Equations for scaling fireball size with yield vary from source to source. The ENW scaling laws for air bursts use the 0.4 power (78):

At t_{min} the fireball radius (meters) = $27\ W^{0.4}$

At breakaway the fireball radius (meters) = $33\ W^{0.4}$

Scaling of fireball dimensions with yield taken to the 0.33 power are also cited in the literature. For example, Mirarchi and Hathaway (135) give the following equation for the average (or effective) fireball radius:

$$\text{Radius (meters)} = 57\ W^{0.33}\ G^{0.5}$$

where G is a form correction factor used when the fireball shape deviates from spherical. For detonations at altitudes where the fireball does not contact the ground, G becomes unity (see ref. 135 for computation procedures for G at lower altitudes).

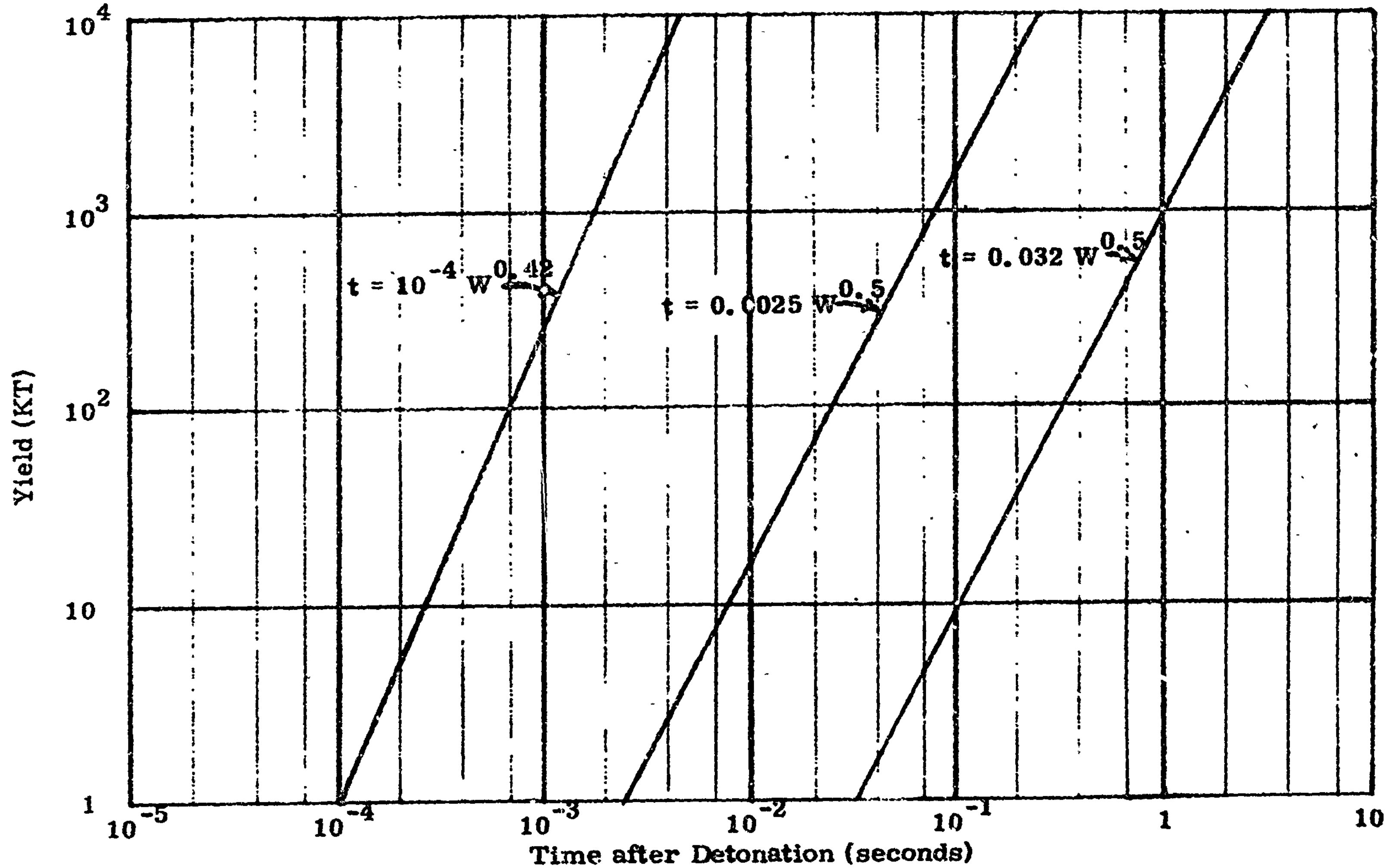

Figure 2 - Time to maximum of first pulse, minimum, and maximum of second pulse as a function of yield.

Lappin (110) cites a fifth power law which he obtained from Edgerton, Germeshausen, and Grier, Inc. (E. G. &G.).* Measured fireball size for a number of surface and low altitude bursts with yields up to 40 KT was used in deriving empirical formulas. For any size weapon (up to 40 KT) at times approaching breakaway, the following relationship can be used:

$$\text{radius (meters)} = 19\, t^{0.4}\, W^{0.2}$$

where t is time in milliseconds and W is yield in kilotons. Other E. G. &G. formulas used were:

At the first peak, radius (meters) = $7.6\, W^{0.368}$

During the second pulse up to 300 ms for fractional KT up to several KT yield, radius (meters) = $35\, W^{0.176}\, t^{0.150}$.

During the second pulse up to 200 ms for several KT up to 40 KT yield, radius (meters) = $(1.8 \times 10^{-3}\, W^3 - 0.105\, W^2 + 2.5\, W + 34.4)\, t^{0.2}$

The maximum fireball size is poorly defined since the shape often deviates from a round or hemispherical form. Maximum fireball radius for a 20 KT and a 1 MT airburst are given as 235 meters and 1,100 meters, respectively, in ENW. Fireball size and apparent surface temperature for a 20 KT yield are plotted in Figure 3. Fireball size computed by the E. G. &G. equations also appear in Figure 3. Agreement between the ENW data and predictions from the E. G. &G. formulas is fairly good up to breakaway, but then the E. G. &G. formulas predict a slower rate of growth.

When extrapolating fireball characteristics from one yield to another differing by a factor of 20 or more, significant errors may be demonstrated using the ENW relationships. For example, ENW reports that fireball

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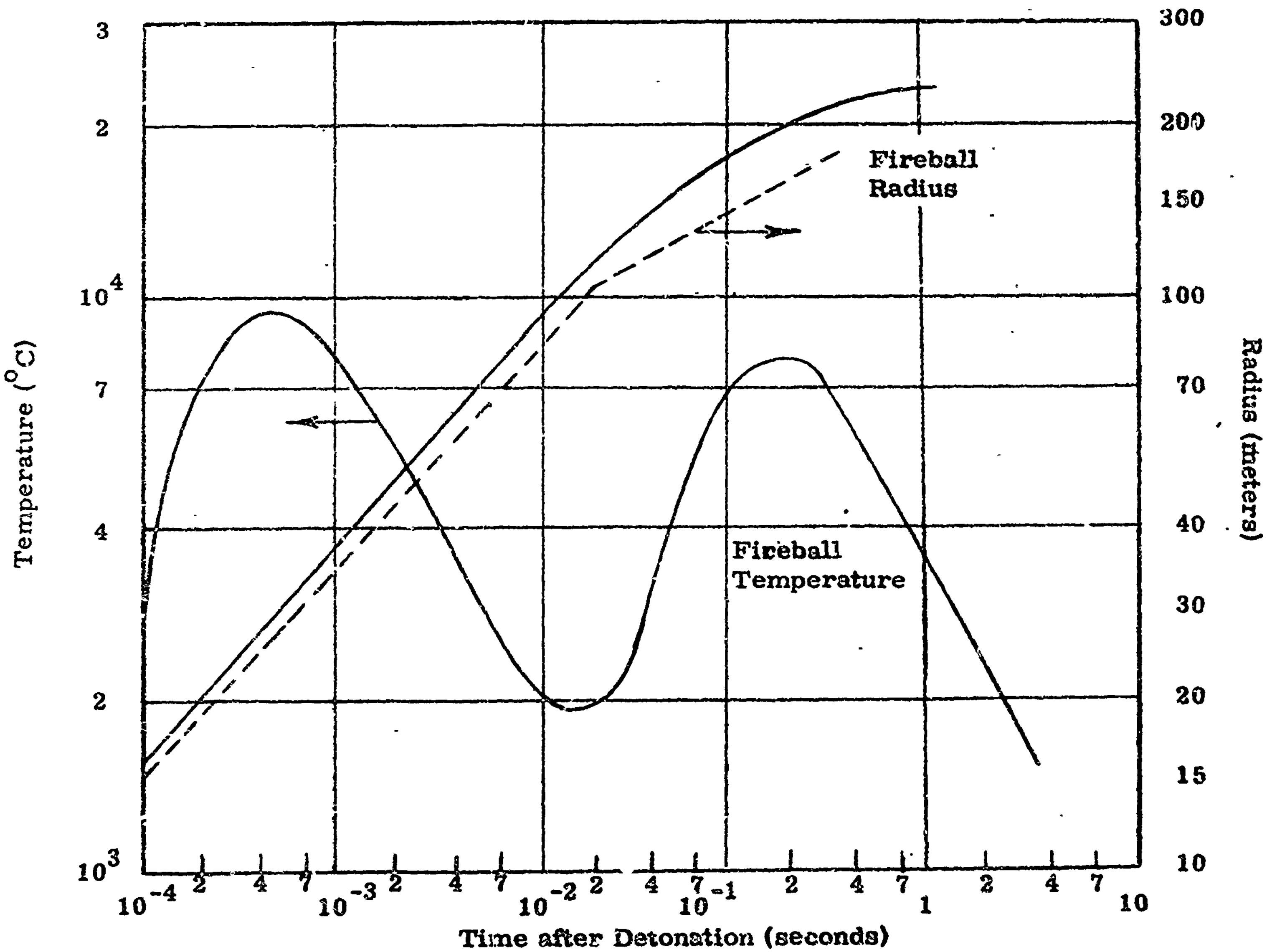
*Communication from D. F. Seacord, Jr., E. G. &G., to Major P. W. Lappin, USAF.



<u>Figure 3</u> - Temperature and radius of fireball from a 20 KT air burst. The solid curves are reproduced from <u>The Effects of Nuclear Weapons</u>, the broken curve was computed from semi-empirical formulas (10a).

surface temperature is essentially constant with yield, time to reach any phase varies as the 0.5 power, and radius varies as the 0.4 power. Therefore, if the formulas are applied to two detonations differing in yield by a factor of 100, the time measures are 10 times as long for the larger, the radius is 6.3 times as large, and the apparent surface temperatures are equal. Thus the total thermal radiation, which varies as the integral over time of the product of surface area and the fourth power of surface temperature would be 400 times larger for 100 times increase in yield! Unfortunately, these relationships have been frequently used to scale from one yield to another, and even programmed into digital computers for predicting chorioretinal burn effects (199). Extrapolation between yields differing by a factor of 20 or more should use modified equations to avoid gross errors in computing the total thermal radiation. For example, if time to reach any phase is considered to vary as the 0.42 power of yield, radius as the 0.33 power, and apparent surface temperature to fall very slightly during the second pulse as yield is increased, total thermal radiation will be directly related to yield.

4. Effects of Altitude

Although the thermal energy for an air burst represents an average of about one-third of the total yield, the corresponding figure for a surface burst is only about 20-30% of the total yield. Fireball development is slower for a contact surface burst, "the respective times are greater by 30% or so"(78). Apparent surface temperatures of the fireball for surface bursts may be quite low, thereby resulting in a higher percentage of energy in the infrared region. Because of the lower thermal yield, longer time development, longer wavelength of the thermal radiation, and increased attenuation from atmospheric components, dust, and debris, the chorioretinal burn and flash blindness hazard is greatly reduced. As underwater or underground burst depth is increased, the chorioretinal burn and flash blindness hazard is further reduced and may be insignficant at even shallow depths.

The relative thermal yield increases with altitude. Length of the thermal pulse varies inversely with the detonation altitude for atmospheric bursts, although the relation is not simple. Below 50,000 feet the classical biphasic emission pattern is observed, with 1 percent or less of the energy in the first phase. At altitudes above 100,000 feet the dip in intensity is less pronounced and at greater altitudes the emission pattern may be represented by a single brief high intensity pulse. Comparison between high and low altitude pulse characteristics are shown qualitatively in Figure 4.

The thermal emission from a megaton range detonation at 250,000 feet (shot TEAK) is nearly complete in less than a second (ENW). The ENW scaling laws predict time to maximum emission rate (T_{max}) of more than a second for low altitude bursts of similar yield.

5. Thermal Emission Rate and Spectra

Although the fireball does not behave as a perfect black body radiator during all phases of development, "the assumption of black body behavior---serves as a reasonable approximation in interpreting the thermal radiation emission characteristics."(78) Energy from a black body radiator is proportional to the fourth power of the absolute temperature:

$$\text{Radiant power (calories/second)} = 1.71 \times 10^{-7} T^4 R^2$$

where T is in degrees Kelvin and R is the fireball radius in meters. The maximum power (P_{max}) occurs by definition at t_{max} and at low altitudes can be approximately computed by the relation (78):

$$P_{max}\ \text{(KT/second)} = 4W^{0.5}$$

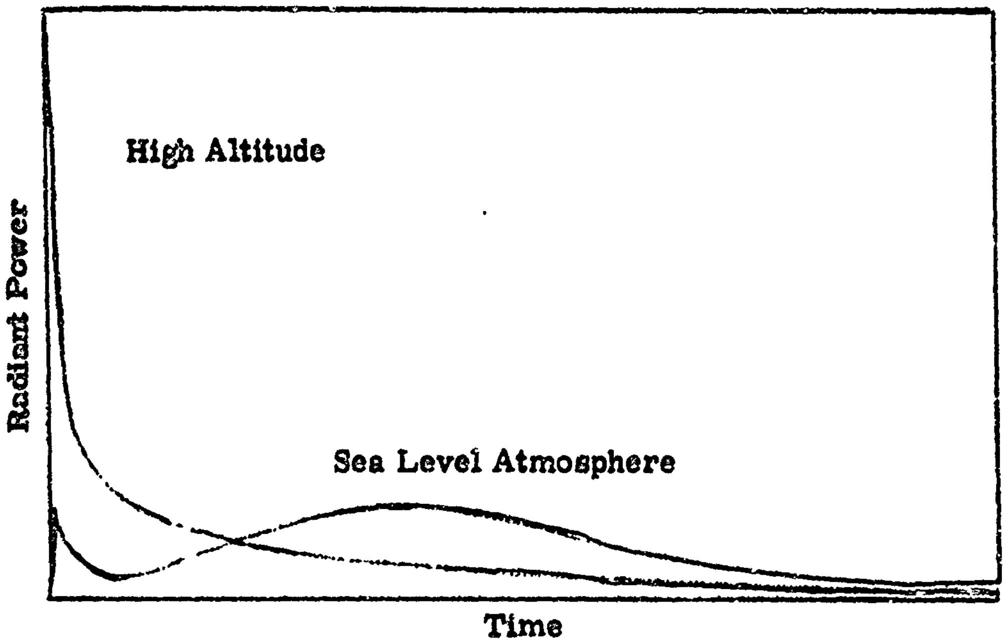


Figure 4 - Qualitative comparison of rates of arrival of thermal radiation at a given distance from high altitude and sea level bursts (from The Effects of Nuclear Weapons) (78).

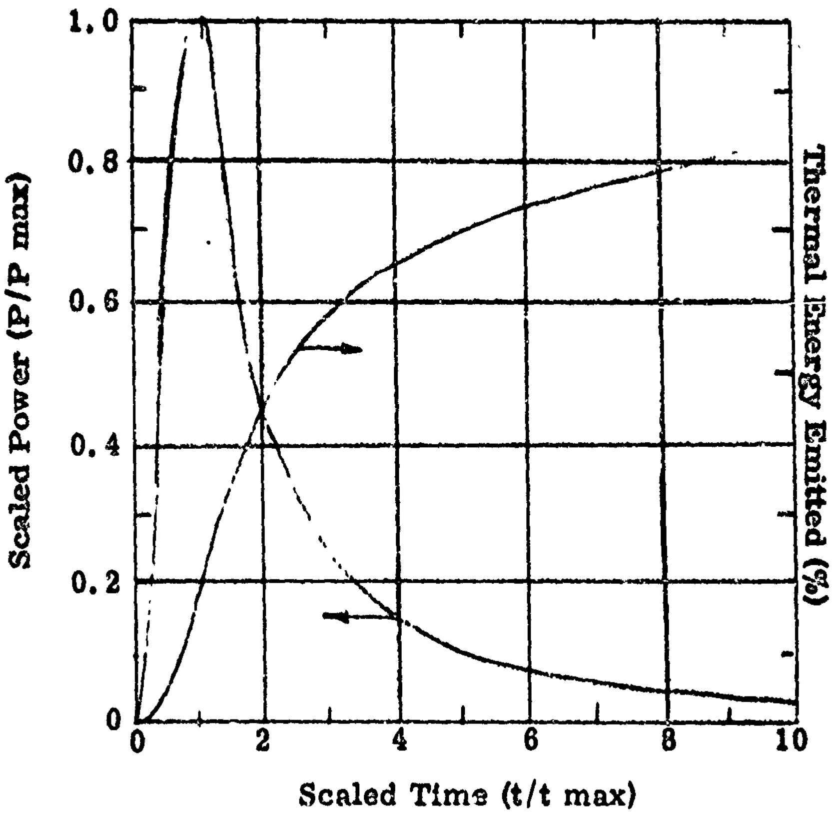


Figure 5 - Scaled fireball power and fraction of thermal energy versus scaled time in second thermal pulse of an air burst (from The Effects of Nuclear Weapons) (78).

Scaled power (power at any time as a fraction of P_{max}) versus scaled time are plotted in Figure 5.

Assuming that the fireball radiates uniformly in all directions, the energy density reaching the cornea (Qc) of an observer located at any slant range (S) may be computed by the relation (78):

$$Qc\ (cal/cm^2) = \frac{10^{12}\ WT}{12\ \pi S^2}$$

where W is the yield in KT, S is the slant range in centimeters, and T is atmospheric transmittance. The above expression assumes that the thermal emission will constitute one-third of the total yield. Since both the image area and corneal exposure vary inversely with the square of the slant range, the retinal irradiance is independent of range, neglecting atmospheric attenuation.

Spectral content of the radiant energy shifts toward the shorter wavelengths as the temperature increases. The wavelength (λm) at which the maximum radiant power occurs for any temperature may be computed from Wien's displacement law:

$$\lambda m\ (\text{millimicrons}) = \frac{2.9 \times 10^6}{T}$$

Radiant power as a function of wavelength appears in Figure 6.

Although the temperature of the fireball is extremely high during the initial pulse, the shorter wavelength (ultraviolet) emission is readily attenuated by the atmosphere. Consequently, at large distances from low altitude bursts, the thermal exposure from the first pulse may be comparatively small. ENW states that "only about 1% of the thermal radiation appears in the initial pulse because of its short duration"(78). However, "---it is capable of producing permanent or temporary effects on the eyes"(78).

Actual measurements 10-18 miles from low altitude nominal yield weapons tests indicated that at ground level 14-27% of the total thermal energy received was in the ultraviolet region (less than 398 mμ), while up to 55% of that measured by aircraft was in the ultraviolet region (83). Attenuation of ultraviolet rays by windows, canopies, and the anterior ocular media is

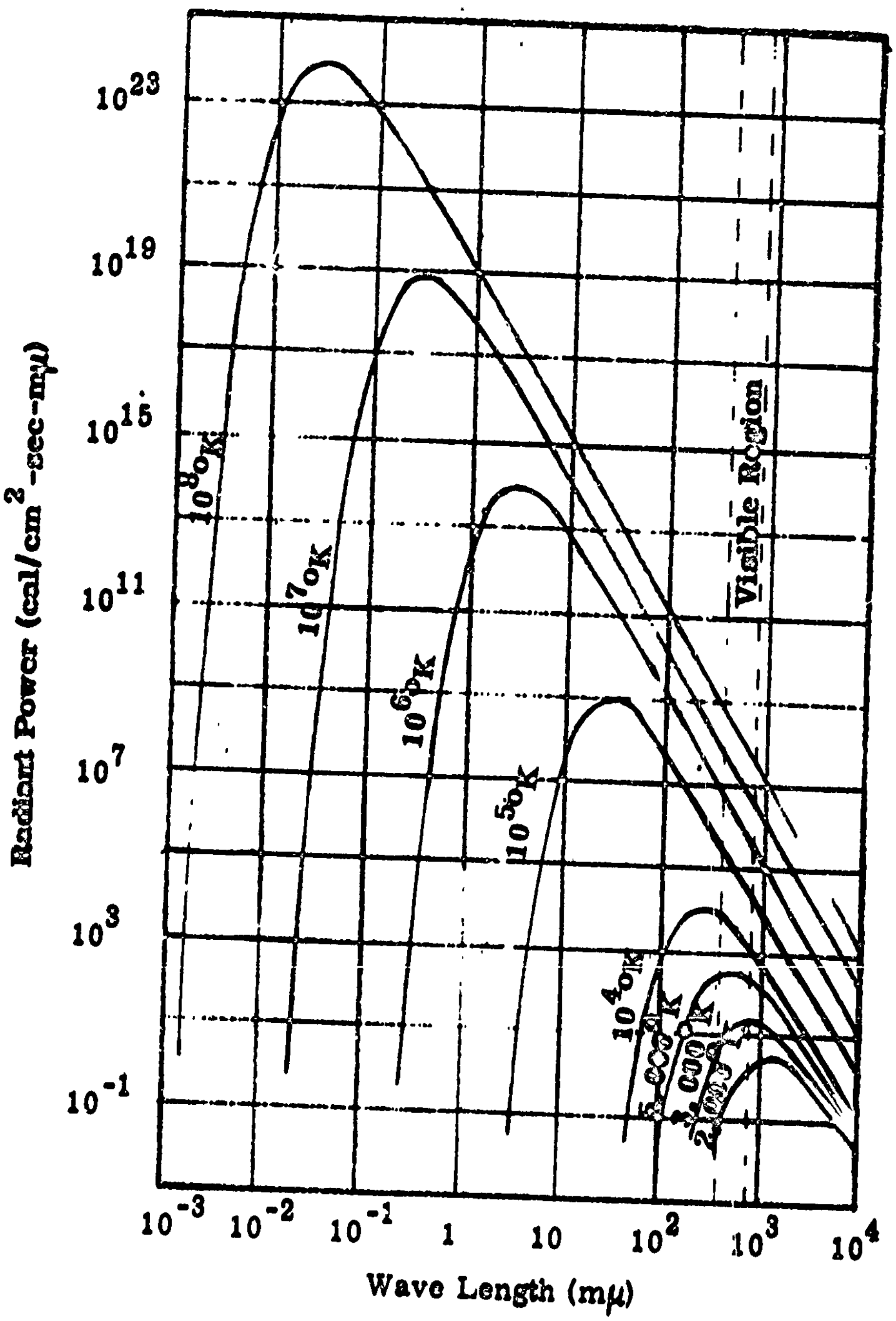


Figure 6 - Radiant power of a black body as a function of wave length at various temperatures. (from The Effects of Nuclear Weapons).

large and must be considered when computing retinal exposure. The relation between maximum thermal irradiance and peak illumination 10-18 miles from low altitude bursts has been found to be approximately linear for nominal yield weapons (83). The observed relation is shown graphically in Figure 7.

A number of mathematical models have been published which quantitatively predict thermal effects on the retina from exposure to nuclear weapon detonations. These models are briefly described in Chapter V. Actual retinal irradiance can be computed by integrating the thermal irradiance at the corneal plane, up to the blink reflex, and correcting for ocular transmissivity and for the ratio of pupil area to image area. Principle differences among the models are in the degree of sophistication of the computation of the pulse and fireball characteristics, atmospheric transmission, and the absorption and distribution of thermal energy in the eye.

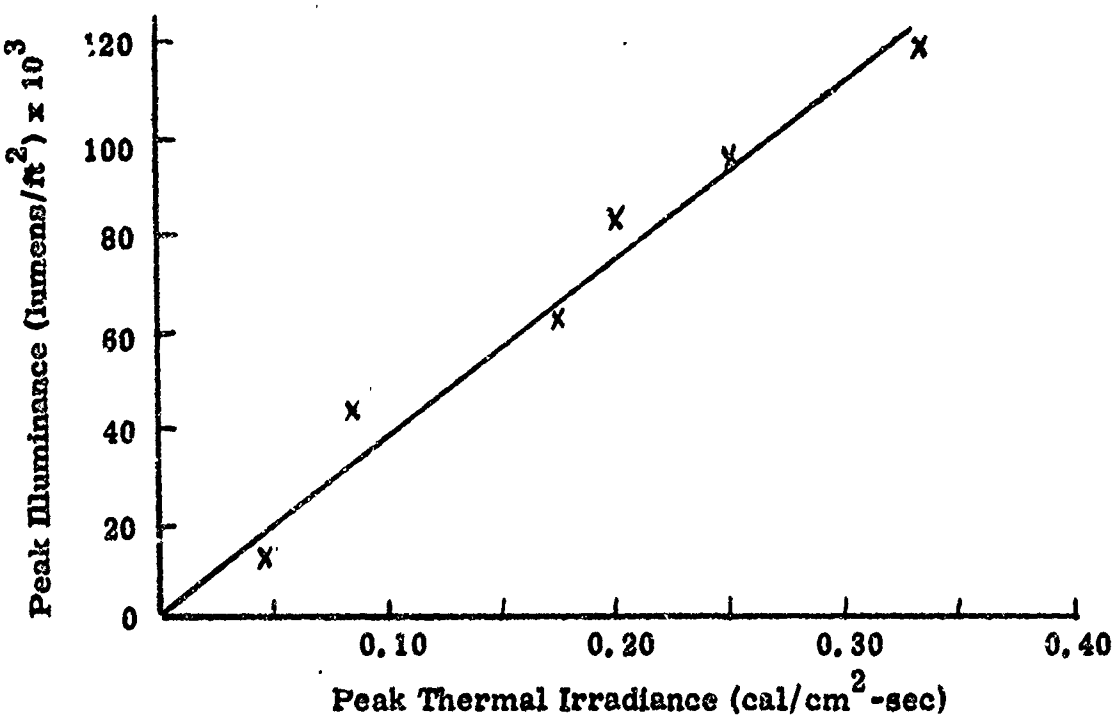


Figure 7 - Peak thermal irradiance versus peak illumination. Crosses represent measurements from five weapons tests (10-75 KT) at distances from 10 to 19 miles (from reference 83).

B. EMR Transmission and Reflection

1. Atmospheric Attenuation

The extent to which the thermal radiation from a nuclear detonation is scattered or absorbed by the intervening atmosphere may significantly influence the flash blindness or retinal burn hazards for distant observers. Because atmospheric attenuation of the incident radiation varies with wavelength, the thermal pulse characteristics measured at different distances from a detonation will vary in both total quantity and quality, or spectral content. Atmospheric attenuation depends on several highly variable meteorological phenomena and therefore may differ widely from one locale to another, or at the same locale at different times. The attenuation can be computed with reasonable precision if measures of density, water vapor, and suspended particulates are available throughout the path.

Thermal energy from a distant source reaches an observer via two major routes, (a) direct radiation, and (b) scattered or reflected radiation. Only the direct radiation (or specular reflection) is of significance for the chorioretinal burn problem. The diffuse reflected or scattered radiation may, however, contribute to the production of flash blindness. The amount of scattering is determined by the number of air molecules (density), and particulates (solid or liquid) in the optical path. Molecular (Rayleigh) scattering preferentially affects short wavelengths, the extinction coefficient varying inversely to the fourth power of wavelength (at sea level the extinction coefficient ranges from 0.0402 km^{-1} at 400 mμ to 0.000268 km^{-1} at 1,400 mμ). The molecular scattering is proportional to air density and therefore decreases exponentially with altitude. Scattering due to particulates varies in a complex manner with wavelength, particle size, and index of refraction of the particles. For maritime atmospheres the presence of greater numbers of larger particles results in scattering which is nearly independent of wavelength. For continental haze conditions the particulate scattering coefficient varies inversely with wavelength, typically ranging from 0.05 to 1.0 km^{-1} (159a).

Atmospheric absorption is due primarily to water vapor. At high altitudes ozone contributes measurably, and certain smoke constituents, if present, may also provide significant absorption at low altitudes. Absorption by water vapor can be computed if the water content (usually expressed as precipitable centimeters) and pressure can be obtained over the optical path. Absorption bands for water vapor are primarily in the infrared.

A number of mathematical models and empirical data have been published which may be used to compute atmospheric attenuation due to the combined effects of the above factors. After having made an extensive review of the literature, Rogers (157) recommended that at the present time the results of Cahill, Gauvin, and Johnson (24) should be used for estimates of low altitude transmissivity. This model produces results which tend to agree with estimates based on experimental data by Gibbons(76, 77) Unfortunately, the Cahill, Gauvin, and Johnson model requires extensive use of computational equipment for obtaining solutions, and should not be used for ranges in excess of the meteorological "visibility". *

Atmospheric transmission factors which appear in ENW generally apply to unusually transparent atmospheric conditions. Values are given as a function of range for several measures of meteorological visibility. ENW predictions and the results reported by Stewart and Curcio (176) provide much larger values of transmissivity than do those computed by Cahill, Gauvin, and Johnson, or estimated from Gibbons' data. Figure 8 is a comparison of these transmission factors. Because of the large differences shown in Figure 8, it is important for the user to understand the assumptions underlying the alternative estimation techniques.

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*Visibility is defined as the distance at which an object can just be detected against the horizon, corresponding to a contrast of about 0.031 at 550 mμ.

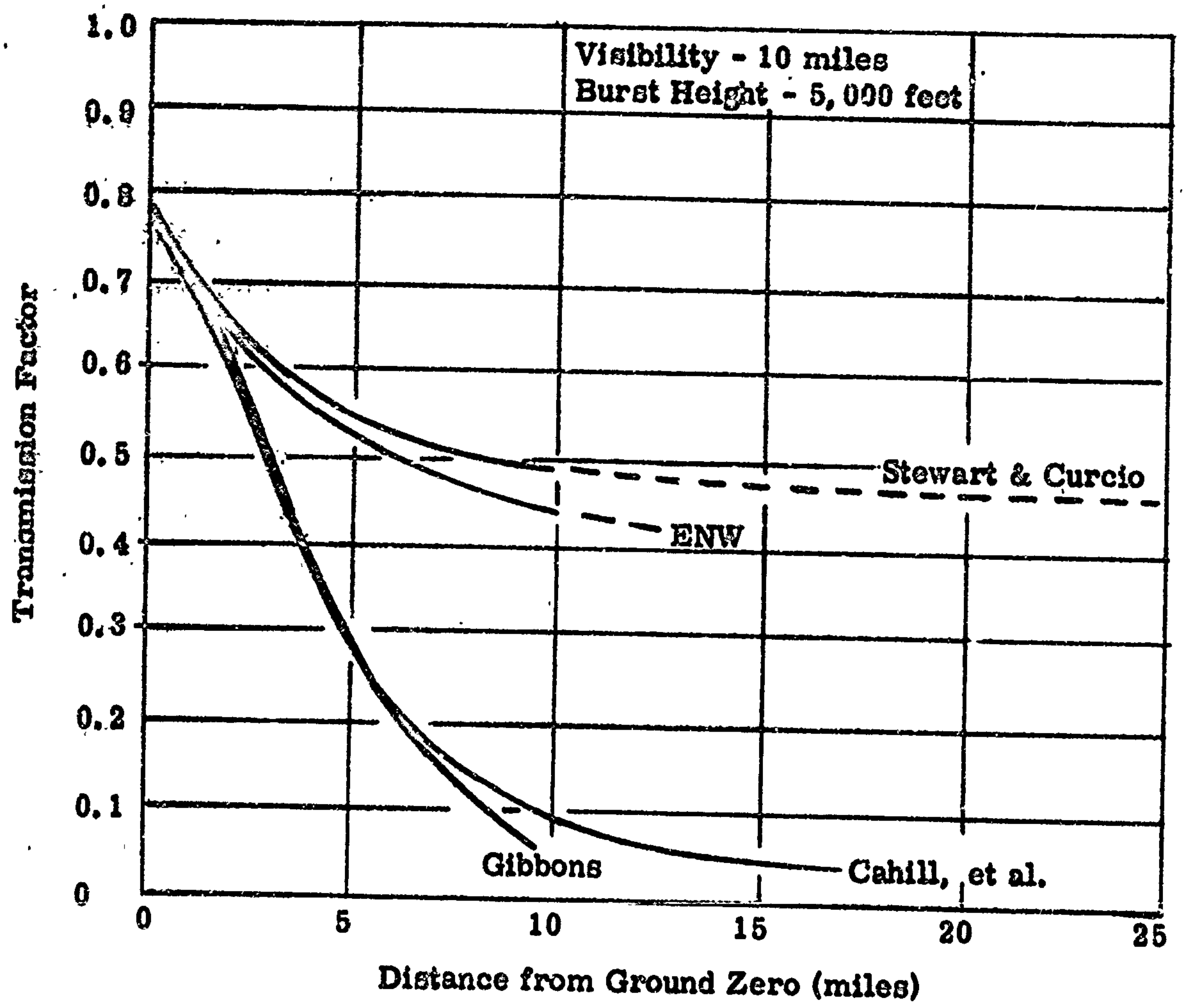

Figure 8 - Comparison of atmospheric (wet) transmission factors derived from several sources (from Rogers, reference 157)

Visibility measures provide an approximation of the scattering coefficient. The atmospheric transmission factor (T) is determined by the relation:

$$T = \exp\left(-3.5\,\frac{D}{V}\right)$$

where D is the distance to the burst measured in the same units as is the visibility (V). Since the density of suspended particulates usually falls off exponentially with altitude, decreasing to negligible amounts at altitudes of 1-2 km, horizontal visibility measures should only be used for detonations which occur at the same elevations as those where the visibility measurements are made.

Elterman (57) has provided a model for atmospheric and ozone absorption from sea level to an altitude of 50 km. Attenuation due to Rayleigh attenuation, aerosol or particulate attenuation, and ozone absorption are tabulated for wavelengths from 270 mμ to 4,000 mμ at altitudes in 1 km increments. The aerosol concentrations used in the computations were obtained from a review of measurements under conditions corresponding to a sea level visibility of 25 km. Calculations for horizontal, vertical, and slant-path transmission between any two altitudes can be readily made from Elterman's tabulations.

A variety of average values for atmospheric attenuation or techniques for computing attenuation. have been used in chorioretinal burn prediction models (see Chapter V). Ham et al. (86) used

$$T = \exp(-kD)$$

where k is a mean attenuation coefficient and D is the slant range. The dose computations presented used a value of 0.1 km^{-1}, "corresponding to a clear atmosphere where the visibility is about 25 miles". The authors point out, however, the extreme criticality of accurate atmospheric attenuation data, and give an example in which a value of 0.1 km^{-1} leads to erroneous results when applied to the "notoriously clear" atmosphere at the

Nevada proving grounds. The large attenuation factors in most parts of the world for normally clear days (0.2 km^{-1}), and around cities (0.4 km^{-1}) are cited as a factor of safety, while the reduced or negligible attenuation from high altitude bursts may lead to burns at "distances limited only by the curvature of the earth"(86).

Wray (197) specifically dealt with the high altitude problem by using a vertical transmissivity of the entire atmosphere of 0.764, and correcting for slant paths by raising the transmissivity value to a power equal to the slant range divided by the altitude. Vertical transmissivities to intermediate altitudes were scaled according to the percent of total atmospheric pressure below the given altitude. Smith (172) used transmission fractions corresponding to 2, 5, and 20 mile visibilities. Transmission values as a function of wavelength were obtained from a literature review and inserted into the equations for predicting exposure. Hoerlin, Skumanich, and Westervelt (96) utilized "reduced height of the atmosphere", or number of normal airmasses in the optical path. After a review of published extinction coefficients at different wavelengths the authors recommended use of an average value of 0.025 km^{-1} for sea level observations of shots "above the atmosphere". Tables relating elevation angle (ϕ) of the detonation to number of air masses ($1/\sin\phi$), reduced height (8 km per airmass), and transmission fraction, corrected for refraction and curvature, were included.

Pickering, Culver, Allen, et al. (153) used a range of assumed attenuation coefficients corresponding to "narrow-beam transmissions at sea level for standard,, clear, dry air of 98, 95, 93, and 90 percent transmission per nautical mile". Different attenuation coefficients were then used for various portions of the path length, corrected for density. The authors described the atmospheric attenuation as a "crude approximation", but questioned the generality of a more sophisticated approach. Their model provided estimates of unscattered radiant exposure for shot TEAK which were only slightly smaller than the measured total at distances out to more than 300 nautical miles. Estimates of direct radiation for shot ORANGE, however, were large in comparison to measured total radiant exposure at long ranges.

Rose (159a) reviewed published measurements and the equations for computing Rayleigh scattering, particulate scattering, and water vapor absorption and then outlined procedures for calculation of total attenuation by five different types of atmospheres (desert, smoggy, maritime, etc.). The resulting equations require use of digital computing equipment for general use.

Wray (198, 199) used a method outlined in the Smithsonian Meteorological Tables to estimate atmospheric transmission in his computer program for the prediction of retinal burns. The technique considers only scattering by pure dry air and by water vapor. Tabular values from the Smithsonian Tables were programmed into the machine and corrected for number of air masses and total precipitable water vapor in the optical path. The effect of water vapor absorption was ignored as "its total effect on the total energy transmitted would be almost negligible" (after atmospheric scattering and pre-retinal ocular absorption and scattering). It was assumed that there was negligible water vapor above 5 miles in altitude. Data were given "for a typical Pacific Ocean atmosphere or a typical winter day at a typical time" Wray emphasized the need for specific data and facts for accurate transmission predictions. The use of average data was described as being "extremely precise and highly inaccurate".

Allen (2) cited the complexity of atmospheric transmission computations and noted the necessity for approximating some of the relevant factors in arriving at a solution. Allen then described an "approximation model" which does not require extensive computer time. Atmospheric transmission is computed as the product of average transmission of: (a) air in the path due to scattering, (b) water vapor in the path due to scattering, and (c) water vapor in the path due to absorption. Average clear dry air scattering transmission ($\bar{T}_{as}$) was computed from:

$$\bar{T}_{as} = \exp(-k_{as}^{eff} M)$$

where "k_{as}^{eff} is the dry air mass scattering coefficient for solar radiation averaged over the effective wavelength spectrum and weighted for black-body radiation at temperature 5800 degrees absolute", and M is the air mass in the optical path. Average water vapor scattering transmission ($\bar{T}_{ws}$) was computed from:

$$\bar{T}_{ws} = \exp\left[-k_{ws}^{eff} W\right]$$

where "k_{ws}^{eff} is a similar weighted average", and W is the mass of precipitable water in the optical path. Both the dry air and water vapor scattering coefficients were averaged from published tables. Absorption by water vapor, according to the author, was "treated rather cavalierly in that it simply is equated to the absorption of solar radiation by atmospheric water vapor with a linear extrapolation for large distances". The total mass of water vapor was computed from sea level measured by assuming an exponential decrease of water content with altitude. It was observed that this assumption fits meteorological data up to 50,000 feet from Christmas and Johnson Islands.

Allen, Culver, and Richey (3a) used the above "approximation model" to calculate retinal irradiance during animal exposures to weapons tests. The predictions were found to be in good agreement with the actual production of burns. Atmospheric transmission was computed from measured air and water vapor densities (as a function of altitude) averaged over a six-month period in the test area.

Lappin (110) has prepared graphical solutions for a model which computes retinal irradiance from low yield or nominal yield weapons during the first 150 ms. For yields less than 3 KT, atmospheric transmission values measured over a 9,700 foot path at the Nevada Test Site were used. For larger yield weapons, the graphs ignore atmospheric transmission.

Muller (136) has used Wray's computer program to prepare a series of yield-versus-distance curves for retinal burn threshold. The program was modified to determine distance for a given temperature rise, and to compute atmospheric extinction coefficients through a haze layer by use of visibility measures. The transmission value as a function of wavelength (T_λ) was approximated by using the following equations:

$$T_\lambda = \exp(-A_\lambda D)$$

where A_λ is the extinction coefficient and D is the optical path length. A_λ is approximated by:

$$A_\lambda = A\,(0.54/\lambda)^B$$

where λ is the wavelength in microns, and A is evaluated by the definition of Visual Range:

$$0.02 = \exp(-AV)$$

$$A = \frac{3.912}{V}$$

where V is the visual range.

The exponent B is obtained from empirical measures of continental atmospheres according to the relation:

$$(0.462/0.636)^B = x/y$$

where x and y are the relative extinction coefficients measured at 0.462 and 0.636 micron.* Muller corrected for conditions other than sea level by multiplying by the density ratio of the given altitude. For those portions of the optical path above the haze layer, use of only the Rayleigh scattering extinction was recommended.

Mirarchi and Hatheway (135) developed a prediction method which includes transmittance equations based on the work by Stewart and Curcio (176).

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*Muller used those reported by W. E. K. Middleton, Vision Through the Atmosphere, U. of Toronto Press, Toronto, 1952, Figure 3.10.

Contributions to retinal irradiance from back scattered radiation and from radiation which has been both reflected and scattered were included. Under certain weather conditions and problem geometry, these factors may be of importance in the production of flash blindness. The transmittance equations presented by Mirarchi and Hatheway require knowledge of the visibility, altitude of the top and bottom of the haze layer, and water vapor partial pressure at sea level. Graphical solutions of transmission versus precipitable water vapor as a function of black-body temperature from 2,000°K to 9,000°K are given.

In summary, it is quite obvious that measurement and prediction of the atmospheric factors which can affect the ocular threat is a difficult problem. The data user is faced with a variety of atmospheric transmission models which differ significantly in their estimation of attenuation of incident energy, especially under conditions where transmissivity is low. Thus the user will be obliged to establish some criteria for the selection of any particular model. The following factors may assist in this selection.

1. The effects of variations in atmospheric composition on burn prediction are less significant when total transmissivity is high, and therefore larger errors will have lesser significance. However, at distances which are equivalent to or greater than the visibility, small errors in estimation of extinction coefficients will have a large effect upon predicted retinal exposure.

2. Precise computational techniques are of little value in determining atmospheric transmission unless equally precise measures of atmospheric density, water vapor content, and particulate properties are available.

3. For purposes of chorioretinal burn prediction, the accuracy of techniques for computing atmospheric transmission should be evaluated against actual thermal measurements, rather than against production of secondary effects which may in turn depend on other unverified variables

2. Seasonal Factors

Frequencies of occurrence of various visibilities, percent cloud cover, and ceilings for several U.S. locations are listed in Table 1. Data are available which may be used to assess the probabilities of various atmospheric conditions on an hourly or seasonal basis. The data in Table 1 were taken from the U.S. Weather Bureau summaries of surface weather observations which are available for more than 900 stations scattered throughout the world. An examination of these meteorological summaries reveals that there are marked seasonal variations in visibility and cloud cover. Other seasonal factors significant to the flash blindness and retinal burn problem are related to the reflectance of the environment. The high reflectance of the snow and ice in comparison to that of water surfaces, vegatative formations, and bare earth (see Table 2) suggests that flashblindness problems will be increased in snow covered environments. In addition, glare ice or snow may produce specular reflections capable of causing retinal burns (see section dealing with reflectance).

Atmospheric attenuation of EMR undergoes seasonal variations, independent of the changes in cloud cover, hazes, or fogs, primarily as a function of the changes in water vapor. Average sea level water vapor undergoes marked seasonal variations, particularly for inland locations. Ranges in excess of 25 to 1 are not unusual for hot humid conditions versus cold winter conditions. Consequently the clear air atmospheric transmission factor may be significantly smaller during the warm moist season. However, wind, fog, clouds, and sources of atmospheric pollution may also undergo seasonal changes which markedly alter the over-all atmospheric transmission. Therefore prediction of seasonal changes in ground level visibility should be made on the basis of statistical examination of meteorological records.

3. Effects of Clouds and Smoke

If there is a cloud layer along the transmission path between detonation and observer, the chance of retinal burns will decrease as the

Table 1

Percentage Frequency of Occurrence of Various Meteorological Conditions*

Location & Period Covered	Mo.	Visibility (miles)				Sky Cover (tenths)			Ceiling Height (thousand feet)			
		0-3/4	1-2 1/2	3-6	7-15	0-3	4-7	8-10	0-0.4	0.5-1.9	2-9.5	10 & over
Boston,	Jan.	3	8	20	69	37	7	56	4	16	22	59
Mass.	Apr.	1	5	14	79	31	11	58	4	17	22	57
1951-	Jul.	1	5	17	76	36	18	46	3	8	14	76
1960	Oct.	2	6	16	75	43	11	46	5	12	18	66
Topeka,	Jan.	3	4	8	85	38	14	48	3	14	12	71
Kansas	Apr.	-	2	6	92	35	13	52	-	14	26	61
1950-	Jul.	-	2	7	92	43	20	37	-	6	19	76
1955	Oct.	-	1	5	93	56	14	30	-	8	12	80
Macon,	Jan.	4	7	27	63	36	14	50	7	17	17	59
Ga.	Apr.	1	2	15	82	47	18	34	2	12	15	71
1942-	Jul.	-	1	10	88	38	24	38	2	11	18	70
1952	Oct.	1	3	20	76	53	13	34	2	11	13	74

*U.S. Weather Bureau Summaries.

Table 2

Reflectance Factors for Natural Objects (from 135)

Water Surfaces	%
Inland water	5-10
Ocean	3-7
Rough water (white caps)	10-31

Bare Areas and Soils	
Snow (fresh fallen)	70-86
Snow or ice	46-90
Granite	12
Mountain tops (bare)	24
Sand (dry)	18-31
Sand (wet)	9-19
Clay soil (dry)	15
Clay soil (wet)	7-9
Field (dry plowed)	20-25

Vegetative Formations	
Coniferous forest (summer)	3-10
Deciduous forest (summer)	10
Deciduous forest (fall)	15
Meadow (dry)	3-8
Desert	24-38

Clouds	%
Very dense clouds	78
Dense, nearly opaque	44
Thin	36-40
Stratocumulus	56-81

Altostratus	
(occasional breaks)	17-36
(overcast)	39-59
Cirrostratus, overcact	44-50
Stratus, 600-1,000 feet thick	78

percentage of cloud cover and thickness of the clouds increase. By contrast, the flash blindness threat may actually increase (see section of Flash Blindness). If the observer and the detonation are both at the cloud layer altitude, the probability of unrestricted visibility is computed as follows (2):

$$\text{Probability} = \exp\left(-\frac{4FS}{\pi d}\right)$$

where F is the fraction of sky cover, S is the horizontal distance to detonation, and d is the average diameter of clouds. Thus if there is one-tenth cloud cover, the chances of unobstructed visibility are less than 8% for horizontal distances of about 20 cloud diameters. If the detonation occurs within the altitude range of the cloud layer, but the observer is located above or below the layer, replace S in the equation by S^1.

$$S^1 = \frac{L-H}{O-H}$$

Where H is the altitude of the detonation, L is the average altitude of the surface (upper or lower) of the cloud layer along the transmission path, and O is the altitude of the observer. Similarly, if the observer and detonation are respectively above and below the cloud layer (or vice versa) S^1 is computed as follows:

$$S^1 = \frac{\text{thickness of cloud layer}}{O-H} \times S$$

Transmittance through the clouds is extremely variable. Although much of the thermal radiation may be transmitted through the cloud, scattering will generally prevent observation of a fireball image. Consequently, thick clouds may protect against retinal burns, but not against flash blindness. Rogers (157) cites the following transmission factors for scattered plus direct energy through clouds:

Altitude of Cloud	Transmission Factor
High clouds (mean lower level = 20,000 feet)	0.65-0.85
Middle clouds (mean upper level = 20,000 feet) (mean lower level = 6,600 feet)	0.4-0.55
Low clouds (mean upper level = 6,600 feet) (mean lower level = close to ground)	0.15-0.35

Typical cloud cover data for several representative U.S. locations are reported in Table 1. The over-all transmission factor will be the product of the transmission factors through the clouds and through the intervening atmosphere.

In addition to the attenuation and scattering effects of clouds, the reflectance of thermal energy from clouds may contribute to flash blindness production. Reflective factors for a variety of cloud types are included among those tabulated in Table 2.

Goodale, Hawkins, and Willoughby (79) recently reviewed the theoretical factors affecting the interaction of thermal radiation with smoke screens. The efficiency of certain smoke screens in attenuating thermal radiation from nuclear weapons was found to be sufficiently high to warrant consideration of use of artificial smoke screens to protect metropolitan areas. The interaction of suspended particulates with the thermal energy is expressed in the form of absorption and scattering coefficients (the total extinction coefficients minus the scattering coefficient equals the absorption coefficient). The fraction (f) of incident radiation that passes through a screen without any interaction decreases exponentially as the extinction coefficient (K_e) and thickness (Z) increases:

$$f \approx \exp\left(- \frac{N \pi a^2 \, KeZ}{\mu} \right) = \exp\left(- \frac{3 \, m \, Ke}{4 \mu p_a} \right)$$

where a is the radius of approximately spherical particles, N is the number of particles per unit volume in the screen, μ is the cosine of the angle between the incident radiation and the surface normal, m is the mass of the particulate material per unit area of the surface of the screen, and p is the density of the particulate substance.

Screens composed of absorbing particles having the same extinction coefficients as that of a scattering screen will transmit less diffuse light. Consequently, smokes composed of such absorbing materials as carbon particles are better suited to thermal countermeasure applications than are scattering aerosols (such as oil mists) Goodale, et al. (79), report that carbon smoke produced by the U.S. Army IRS-E32 Black Smoke Pot will attenuate thermal radiation from a nuclear fireball as follows:

Pounds Per Square Mile	Transmission Factor.
1,000	0.50
2,000	0.25
4,000	0.06
6,600	0.01

The above figures apply when the incident energy is normal to the smoke screen surface.

4. Reflected Energy

Both diffuse and specular reflections from objects and surfaces should be considered in assessing the flash blindness threat. However, only the specular reflections will usually be capable of producing chorioretinal burns. Reflecting characteristics of surfaces commonly found in civilian and military environments vary from completely diffusing surfaces through a continuum of varying degrees of highlights to those surfaces which perfectly reflect images. In addition to the nature of the reflection, there is a wide range in the amount of energy reflected. Reflection factors may also vary with wavelength and with the angle of incidence. The geometry of the reflecting surface, source, and observer locations are particularly important in determining the hazard of chorioretinal burns from curved reflecting surfaces such as automobile bumpers and trim. The preceding considerations indicate that the effects of reflections will be almost impossible to predict in many situations, and impractical to predict for populations except on a statistical basis. The fact that it is not uncommon to be annoyed by specular reflections of the sun off surrounding automobiles, or trim on your own automobile while driving during sunny days, indicates the potential magnitude of the reflection problem.

For small angles of incidence (light source nearly perpendicular to reflecting surface), the reflectance factors of wall board painted with flat paints are greater at the red end of the spectrum than at the shorter wavelengths. Reflectance factors for a variety of colors have been reported to vary from 21% to 86% (average 59%) when illuminated by a tungsten filament lamp. When illuminated by a mercury vapor lamp, the range of reflectance factors varied from 9% to 81% (average 49%). White paints reflected the larger amounts and dark greens the least among those tested.

Common flooring materials such as bright-colored linoleum and asphalt or rubber tiles may reflect as much as 70% of 700 mμ light and average 50% across the visible spectrum. Measured reflectance factors appear to be more dependent on color than on materials. Highly-polished floor surfaces may produce highlights having an apparent brightness nearly as great as that of the source, particularly at large angles of incidence. Thus, flash blindness or even chorioretinal burns could occur indoors from floor reflections. Polished metal fittings on windows may be a source of specular reflections. The gently curving surfaces of plastic chairs may produce focused reflections having an apparent brightness greater than would be anticipated on the basis of their reflectance factors alone.

Reflecting surfaces have been a major source of complaints by pilots for years. Recently, a military flier reported (103) that even in modern aircraft "the reflection of sunlight off the glass covers of aircraft flight instruments often prevents the instruments from being readable". Greater care should be devoted to improving the reflecting characteristics of military equipment, but such personal items as wristwatches should not be ignored since they could also be a dangerous source of specular reflections. The hazards of reflected energy in producing flash blindness or chorioretinal burns among the military during nuclear attack could be greatly reduced by a concerted effort to eliminate polished surfaces or to redesign equipment where reflective materials must be used.

It has been conjectured that accidental chorioretinal burns experienced by two military personnel during Operation FISH WL in 1962 may have been due to specular reflections from a high altit de detonation (42, 43a).

Whiteside (192) reported a sensation of "dusi in his eye caused by the light of a nuclear detonation reflected from highly reflective sand. He compared this sensation to that in the eyes following exposure to high intensity ultraviolet radiation. Symptoms attributable to ultraviolet irradiance of the eyelids were also present. Only one eye was exposed and the symptoms were confined to this eye. During a later experiment, Whiteside directly viewed the fireball and again experienced the same symptoms. Reflection factors for a variety of natural surfaces appear in Table 2.

Reflection factors for several manufactured materials appear in Table 3. In assessing the extent of chorioretinal burn or flash blindness hazards from reflections in any situation, the following variables must be considered:

a. The nature of the surface--color, condition (dirt, dust, oxide coating), curvature, area (for diffusing surfaces), and material.

b. The situation geometry--deviation from the angle of reflectance, angle of incidence, distance of observer from the surface, number of reflecting sources in the field of view, source zenith, and orientation of the observer with respect to reflecting surfaces and the source.

Table 3

Reflection Factors for Manufactured Surfaces

Material	Refer-ence	Wave-length (mμ)	Angle of Incidence	Reflective Factor (%)
Glass	95	Visible	0^{o}	4.65
			20^{o}	4.68
			40^{o}	5.26
			50^{o}	6.50
			60^{o}	9.73
			70^{o}	18.00
			80^{o}	39.54
			90^{o}	100.00
Chrome on Steel	62	300		82
		400		88
		600		90
Aluminum Oxide	62	600		84
		950		88
Stainless Steel 13% Chromium	62	300		47
		400		58
		500		62
		600		67
Vinyl Acetate Lacquer	95	400		90
		500		88
		600		88
		700		88
White Lead Paint (#103)	95	600		76.2
		950		79.3
White Marble (ground, unpolished)	95	600		53.5
Brick - Cream	62	500		4.3
		610		64
		840		69
		1,780		74
Red		500		11
		610		30
		840		37
		1,780		41

(continued on next page)

Table 3 (Cont'd.)

Material	Reference	Wavelength ($m\mu$)	Angle of Incidence	Reflective Factor (%)
Asphalt (Pavement)	62	600		14.8
Granolith (Pavement)	62	600		16.9
White Paper	95	600		71.7
		950		74.7
Linen (starched dull finish)	95	600		81.2

IV. CHORIORETINAL BURNS

A. Introduction

Interest in assessing the threat from nuclear weapons and the safety hazards of laser operations has resulted in considerable research on chorioretinal burn thresholds. Research in these areas is continuing, and results of earlier studies may be revised as better information becomes available. Because of the multiplicity of variables and the multiplicity of measurement units and definitions, comparisons among the data are difficult. The material that follows includes a review of the parameters believed to influence burn thresholds, the mechanisms of damage, some experimental results, and investigative methods.

1. Concentration of Light Energy Due to Focusing

The optical system of the eye is similar in function to that of a camera. The pupil regulates the amount of light which enters the eye, and the lens focuses the light from a source so as to form a well-defined image on the retina. The retinal image is at a minimum size when the focus is optimal. If an object is too close to the eye for proper focus, or the lens is not properly focused, the image will be larger and will be "fuzzy". Unless the object being viewed produces a highly collimated light beam with a diameter which is small in comparison to the pupil size, the amount of light energy concentrated on the retinal image will be proportional to the pupil area. Thus, if the area of a retinal image of a light source is smaller than the pupil area, the amount of energy per unit area on the retina will be greater than that which is incident on the pupil (or corneal plane). On the other hand, if a circular light source subtends a large visual angle (for example, 13^{o} or more with a 4 mm diameter pupil), the image area will be larger than the pupil area and the energy density on the retinal image will be less than that incident on the pupil.

Since the density of thermal or light energy from a nondirectional source varies inversely with the square of the distance from the source, incident energy at the pupil (and the total energy which passes through the pupil) decreases as the distance squared between source and observer. However, the area of the retinal image also decreases with the distance squared for any given object size. Therefore, neglecting atmospheric attenuation, the energy per unit area incident on the retinal image is independent of the distance from a source. This relation holds for all sources which subtend small visual angles as long as the dimensions of the retinal image exceed about 20 microns. For example, a 100 mm circular light source located 8.5 meters from the eye produces a retinal image 0.2 mm in diameter. If the light energy incident on a 6 mm pupil from this source is 0.001 cal/cm^2-sec, the total energy passing through the pupil will be the product of the pupil area and the incident energy per unit area, 2.83×10^{-4} cal/sec. The area of the retinal image is computed to be 3.14×10^{-4} cm^2. Therefore, the energy density on the retinal image is $\frac{2.83 \times 10^{-4} \text{ cal/sec}}{3.14 \times 10^{-4} \text{ cm}^2} = 0.9$ cal/cm^2-sec. If the same light source is moved up to 1.7 meters from the eye, the image diameter will increase by a factor of 5, becoming 1.0 mm, the energy incident on the pupil will increase by a factor of 25, becoming 0.025 cal/cm^2-sec, the total energy through the pupil will be 25 times greater (7.06×10^{-3} cal/cm^2-sec), but the resulting energy incident on the retinal image will still remain 0.9 cal/cm^2. Thus the energy density incident on the corneal surface of the observer changed by a factor of 25 while that on the retinal image remained constant, although 900 times more intense in the first case and 36 times more intense than the corneal intensity in the second case. If the source were moved further away than the initial 8.5 meters, the energy density incident on the retina would remain constant until either or both of two limiting factors became significant: (a) the object becomes sufficiently distant that atmospheric attenuation or intervening objects reduce the incident energy, or (c) the size of the image dimensions approach the point source image spread size as limited by optical imperfections. In the latter case, the energy density incident on the retinal image may be 100,000 times greater than that incident on the cornea.

2. Energy Delivery Rate and Heat Dissipation

Unlike ionizing radiation which may have a cumulative effect when delivered at low rates for long periods of time, light (or thermal) energy does not produce irreversible effects unless the temperature increase in the absorbing tissues exceeds some critical value. Since absorbed heat will be carried away by conduction, the rate of delivery of thermal energy must exceed some threshold value before a damaging temperature rise can occur. Prolonged exposure to light levels typically experienced in homes and offices does not produce injurious retinal temperatures. Chance viewing of the solar disc infrequently produces permanent damage. Prolonged viewing of the solar disc is generally made through a constricted pupil so that the rate of energy delivery is low enough to cause only a gradual rise in temperature of the absorbing retinal layers. If the exposure ceases within several seconds, the heat is conducted away and no damage results. If the exposure continues, the temperature rises, which causes the rate of conduction to rise, and the temperature increases at a decreasing rate. Damaging temperature levels may be reached in less than a minute if the exposure continues.

In reviewing the various reports on chorioretinal burns, the reader should be particularly alert to the manner in which the dose is specified. Irradiance is usually expressed in cal/cm^2-sec, but may be expressed in other units which indicate a time rate of delivery (see Section XI, Glossary and Conversion Factors). Exposure is usually expressed in cal/cm^2, the integrated irradiance over the pulse length. Since the pulse length may vary with the method of measurement (pulse shape varies from study to study), computation of the integrated dose may not be a simple procedure and the reader should determine the definitions and procedures employed before attempting to generalize from the data.

B. Thresholds for Irreversible Damage and Relation to Variables of Time, Size, Intensity, and Absorbed Dose

By definition, threshold exposure is a differentiation between the amount of absorbed energy which will produce a definite retinal burn as opposed to any amount of absorbed energy below this amount which will not result in the production of a burn. This is, of course, a grossly oversimplified concept and it is necessary to further define the variables which influence the threshold limits and the criteria which describe the presence or absence of a burn. First the end points must be defined; i.e., threshold amount of energy necessary to produce a measurable visible lesion or that amount of absorbed energy necessary to produce an acute functional disruption of vision. The initial phase of this review will be limited to thresholds for irreparable damage, recognizable in terms of field defects for humans or by ophthalmoscopic examination in the case of animals, and to the principal modifying factors. These modifying factors include the following:

1. Corneal irradiance produced by the source (cal/cm^2-sec)
2. Size of the source (visual angle which it subtends)
3. Spectral characteristics of the source (power density as a function of wavelength)
4. Attenuation of the source energy by intervening filters, limiting apertures, etc.
5. The duration of exposure and pulse characteristics
6. Pupil size
7. Spectral absorption, reflection, and scattering characteristics of the optic media
8. Degree of accommodation of the lens
9. Degree and type of pigmentation of the retinal layers

10. Variations in eye structure between species used in establishing thresholds

11. The criteria used to assess burn/no burn threshold dose (for example, the criteria may be the dose at which 50% of the exposed animals received burns, or it may be the highest dose for which no burns were observed).

1. The Degree of Pigmentation as a Modifying Factor in Threshold Determination

Large individual differences have been reported (74) in the development of chorioretinal lesions following exposure to given amounts of energy (test animals exposed under identical experimental conditions). These differences are not restricted to species variations, but include differences from animal to animal within the same species, from eye to eye in the same animal, and even from locus to locus within the same eye (hot spots). The reflectance and absorption of light energy depends on the degree and type of pigmentation, and it is believed that variations in pigmentation largely account for the observed differences between and within test animals. Rounds (161) and Malt (120) corroborated this criticality of the degree of pigmentation in their studies on the effects of laser irradiation on cells in culture. Malt found that 6 cal/cm^2 would kill pigmented cells but would spare unpigmented cells. Short-duration (30 nanoseconds) pulses of about 1.9 to 2.4 cal to human retinal cells containing 0 - 5 pigment granules were without effect while the same amount of energy per unit time immediately killed cells containing 20 or more pigment granules. The addition of artificial pigments (stains) enhanced the effect of a given amount of energy, and specific subcellular components of more intense pigmentation could be selectively destroyed. Jacobson, et al. (111) also reported in their retinal burn studies that degree of choroidal pigmentation was found to be a critical factor. Rose (114) compared the threshold energy from a laser beam (700 mμ) needed to produce a recognizable chorioretinal burn in light, medium, and dark pigmented rabbit eyes and found that thresholds varied by a factor of 5 from dark to light pigmentation. Bredemeyer, et al. (11) measured "spectral effectiveness coefficients " (E λ) for rabbits for that portion of the retinal tissue first struck by radiation and for the entire thickness of the choroid. The coefficients vary with degree of pigmentation, but maximum differences deviate by less than a factor of two from light to heavy pigmentation (see Figures 9 and 10).

Geeraets, et al. (72) compared the spectral absorption characteristics of different structures in excised human and rabbit eyes. At the gross level (i.e., intact tissue layers rather than isolated cells), absorption in the retinal pigmented layer and/or the vascularized, pigmented choroid is nearly 100% for wavelengths up to 500 mμ, then gradually decreases to 30% at 1,150 mμ. Following this, absorption increases rapidly to nearly 100% at 1,500 mμ. Geeraets, et al., also measured light transmission through the ocular media, and reported that the transmission extends from 400 - 1,400 mμ. The transmission curve has several peaks, rising rapidly as the wavelength is increased above 400 mμ until it exceeds 80% from 500 - 950 mμ, then dips to about 40% at 1,000 mμ before rising again to better than 80% at 1,100 mμ, then falling to less than 20% at 1,250 mμ, and trailing off to a negligible quantity by 1,400 mμ.

Boettner and Wolter (13a) measured the transmittances of each component of the ocular media of the human eye and reported total values somewhat lower than those reported by Geeraets and co-workers. The direct transmission was found to extend from 400 to 1,350 mμ, ri[illegible] sharply above 400 mμ to about 25% at 410 mμ, then more slowly until a peak of 54% is reached at about 790 mμ, then dipping to 20% at 980 mμ, rising to 40% at 1,100 mμ, then falling to 5% between 1,200 and 1,300 mμ, and falling to a negligible amount above 1,300 mμ. When scattered transmission is included with the direct values, the total transmittance reaches higher values for all wavelengths from 400 to 1,300 mμ but still remain lower than those reported by Geeraets, et al. (for example, 83.5% versus 96% at 700 mμ).

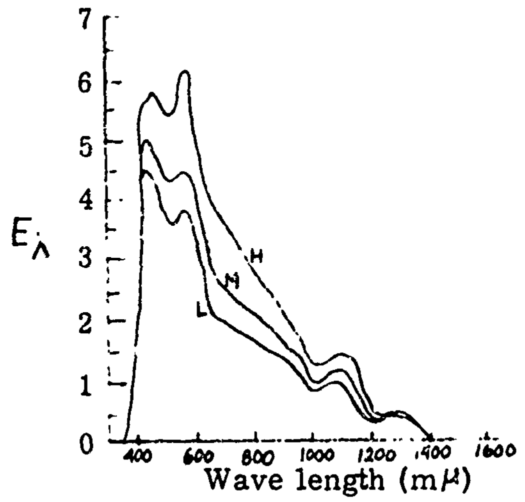

Figure 9 - Percent light absorption (spectral effectiveness coefficients, E_λ) in 25% thickness of the chorioretinal tissue with 0.1 mm additional blood, for Light (L), Medium (M), and Heavy (H) degrees of pigmentation (from Bredemeyer, et al., reference 11).

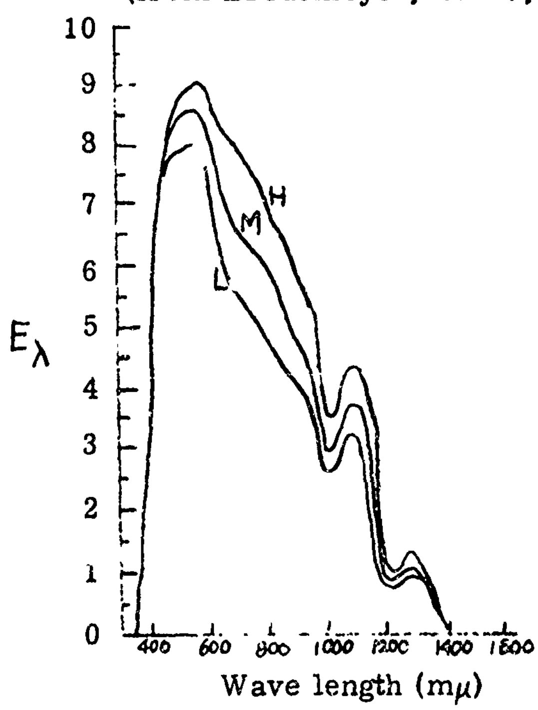

Figure 10 - Percent light absorption (spectral effectiveness coefficients, E_λ) in full thickness of the chorioretinal tissue with 0.4 mm additional blood, for Light (L), Medium (M), and Heavy (H) degrees of pigmentation (from Bredemeyer, et al., reference 11).

2. Effects of Spectral Variations in the Incident Energy

Since the various biological pigmented materials have characteristic absorption bands, it is apparent that the wavelength of the incident light is a critical factor in the determination of threshold. Peak absorption of 500 to 550 mμ correlates with maximum damaging effectiveness of light energy. Thresholds measured using ruby lasers (emission at about 700 mμ) will differ from those measured using a source which radiates near 500 mμ(11). Use of filters on the source to remove inefficient energy will decrease the threshold corneal irradiance which produces a burn. However, measurements reported as absorbed retinal doses should be independent of the source spectral characteristics.

Transmission and reflection of the incident energy as a function of wavelength is also an important consideration in source efficiency. Since reflection from and path length through the ocular media depend on the angle of incidence, these factors may be expected to become more important as the angle of incidence of the light energy on the cornea increases.

3. The Size of the Field Irradiated (Retinal Image)

By analogy with the thermodynamics of nonliving materials, it would be expected that as the size of the area irradiated increases, the dose rate (cal/cm^2-sec) to produce a given temperature increase would decrease. However, diverging results have been published regarding chorioretinal burn threshold as influenced by image size (other factors constant). Ham, et al. (86) measure thresholds for different combinations of image size and exposure time, and observed a decreasing threshold level with increasing image size (in terms of cal/cm^2). On the other hand, Jacobson, et al. (100) also measured thresholds for different combinations of image size and exposure time and observed a decreasing threshold level with decreasing image size. Ham studied image sizes ranging from 0.18 to 1.1 mm diameter while Jacobson used 0.7 to 4.0 mm diameter retinal images. Interestingly enough, these two studies are in agreement for image sizes of about 1 mm in diameter. The thresholds at 1 mm diameter have also been independently verified by Bredemeyer, et al. (11). Thus, if results of these studies are correct, there is an optimum image size at which the burn threshold is a minimum! It would seem to be particularly important to verify this effect in a single study employing a wide range of image sizes. Such a study has been planned by the School of Aerospace Medicine.

Departures from reciprocity at threshold have been observed for a variety of image sizes, irradiances, and exposure durations (54, 60). The deviations from reciprocity become less pronounced as image sizes are increased or as exposure duration is reduced. Burn threshold data in terms of retinal irradiance versus exposure time are plotted as a function of retinal image size in Figure 11. For exposures longer than 20 ms, reciprocity holds for large image size but not for small image size. A more recent report by Geeraets and Ham (74) extended exposure time down into the microsecond and even into the nanosecond region where further departures from reciprocity were observed (see table on page 56).

Burn threshold data in terms of absorbed radiation versus exposure time were computed from Ham's data by Bredemeyer, et al. (11) and verified experimentally at several exposure times. These data are plotted for several image sizes in Figure 12.

Because of imperfections in the optical qualities of the eye, light from a point source is distributed over a finite minimum area, the size depending on a number of factors. A circular image with a radius of 10 microns may be used to compute the intensity of energy of light at the center of the image formed by a point light source radiating over a broad spectrum (121). This peak intensity falls off readily to half value at a radius of about 4 microns.

4. Length of Exposure Time

Threshold doses for the production of minimal irreversible chorioretinal burns are dependent on the length of time over which the

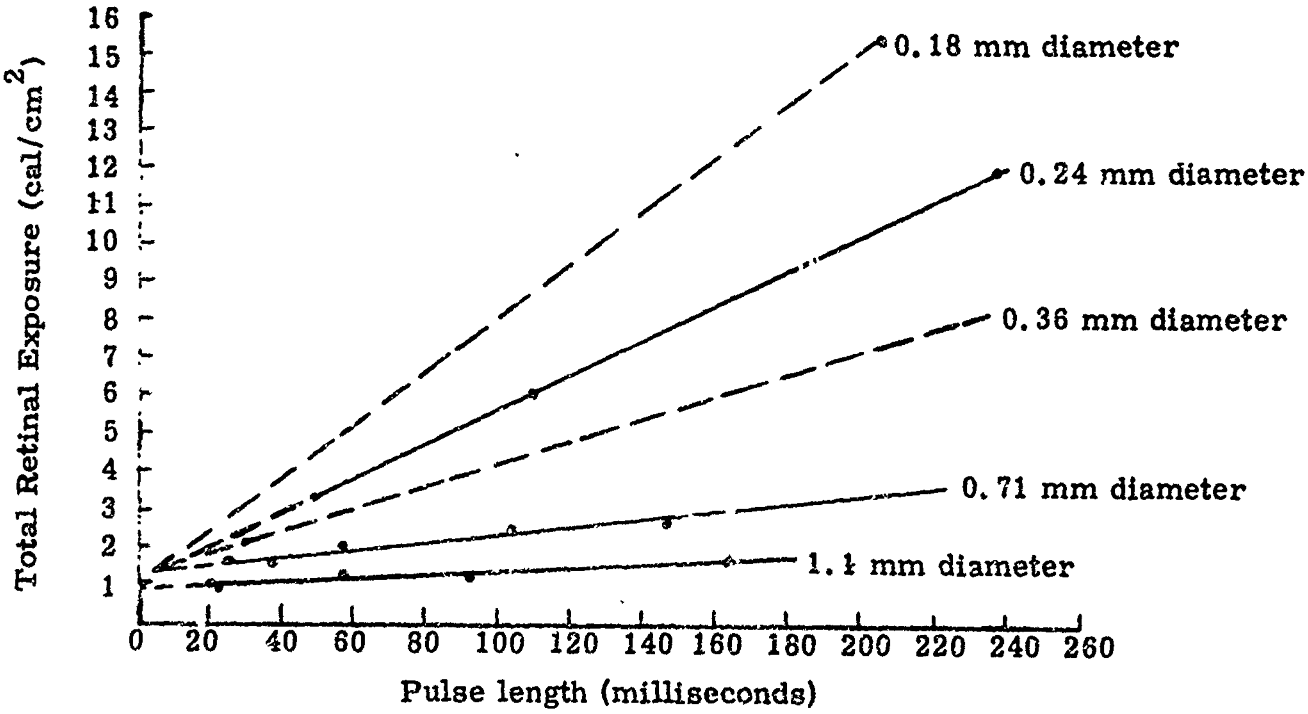

Figure 11 - Threshold exposure as a function of pulse duration with several image diameters (from Ham, et al., reference 86).

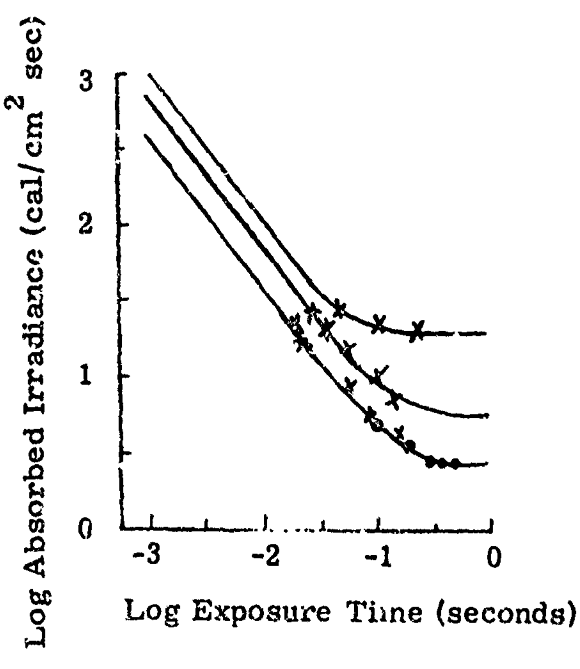

Figure 12 -Threshold for absorbed radiation versus time for several image sizes. Data from Bredemeyer, et al. (reference 11) showing agreement between their data (circles) and that reported by Ham, et al. (X'es).

dose is received. This dependency is of increasing importance as image size decreases and exposure time increases (11, 86). As exposure time lengths are increased, the dissipation of thermal energy from the image to surrounding tissues increases in significance. At low levels of irradiance, the dissipation rate may equilibrate with the energy absorption rate and the temperature stabilizes at a level below that necessary to produce biologic damage. More refined thermal burn models are needed which precisely define the relationships between irradiance, area, and length of exposure. As more data become available, existing models are being improved.

That the relationship between exposure time and threshold irradiance deviates appreciably from perfect reciprocity at low levels of irradiance with long exposure times has been known for some time (see Figures 11 and 12). However, recent experiments have also indicated appreciable deviation from reciprocity for pulse lengths in the microsecond range and below. Geeraets and Ham (74) reported decreasing threshold doses as exposure time was reduced from 30 ms to 0.03 μs.

Source	Exposure Time	Retinal Threshold Exposure
Photocoagulator	30 ms	0.96 cal/cm^2
Laser	200 μs	0.17 cal/cm^2
Photocoagulator	175 μs	0.16 cal/cm^2
Laser	0.03 μs	0.017 cal/cm^2

The distribution and dissipation of heat is poorly understood for pulses of such short duration. Earlier reports had extrapolated thresholds to short pulse lengths on the assumption that reciprocity would hold below the 10 - 30 ms range, and estimates based on this assumption should no longer be used. For example, the curves originally presented by Bredemeyer, et al. (11) were extended down to 1 ms pulse lengths on the basis that "It is assumed that the reciprocity law holds for very short pulses".

5. Extrapolation of Animal Data to Humans

Although there are many similarities between the eyes of experimental animals and humans, there are also significant differences. In the rabbit, one of the principal experimental animals for the study of chorioretinal burns, the ocular media has been shown to transmit approximately 10% more light than excised human eyes (72). The focal length of the rabbit eye, 10 mm average, is significantly less than the 17 mm average for the human eye. Since image diameter varies directly with focal length for distant objects (distance large with respect to focal length), the image diameter will be 70% greater on the human retina (38, 188). Since the area of the retinal image varies as the diameter squared, the area will be 3 times larger and the retinal irradiance only one-third that received by the rabbit (assuming equal pupil size). Eye-blink time for the rabbit averages 300 ms compared to 150 ms for humans.

Both rabbits and monkeys were used in two weapons test series to evaluate chorioretinal burn production. Since exposure conditions were equivalent for the two species, important interspecies differences should be evident from the data. In the first test series, 3-1/2 year old Macaca rhesus monkeys weighing about 8 pounds were compared to pigmented rabbits weighing 5 to 7 pounds (58). Blink times were measured photographically. Average blink time for 8 monkeys was 160 ms (range was 109 to 312 ms) compared to an average of 382 ms (range was 289 to 437 ms) for 6 rabbits located approximately eight miles from a low altitude, low yield detonation. At a distance of between seven and eight miles from an intermediate yield detonation at the same altitude, blink time for 8 monkeys averaged 293 ms (range was 109 to 672 ms) compared to an average of 362 for the rabbits (range was 250 to 454 ms). From the observed incidence and size of lesions, no burn threshold differences were apparent. Individual differences in blink time were larger among monkeys than among rabbits. In the 1962 test series, Macaca mulatta monkeys were compared to rabbits (2). Photographic records indicated that a number of the animals' eyes closed at very short measured times after detonation (values as low as 50 ms were reported for the rabbits and 80 ms for the monkeys). Such unexplained short intervals are not likely to represent valid blink reflex times. Differences between effects on different species were observed to be related to pulse duration. Very high altitude detonations and low yield, low altitude detonations did not produce apparent differences in burn incidence between rabbits and primates. However, for very large yield atmospheric bursts, the rabbits blinked and generally kept their eyes shut, while the monkeys repeatedly opened and closed their eyes (2). The blink reflex provided a high degree of protection for the rabbits, but the monkeys received multiple burns due to multiple reopenings of the eye during the second thermal pulse (as many as 12 separate burns were counted for a single monkey).

Geeraets, et al. (72) measured the loss of light energy in the retina and choroid for rabbits of differing degrees of pigmentation. These values were then compared to measurements taken from two human eyes (obtained from a 28-year old male). The data should be cautiously interpreted since some visible changes were evident in the human eyes at the time of the measurements (four hours post-mortem). The rabbit eyes were measured 30 minutes after enucleation and are believed to accurately represent <u>in vivo</u> transmission characteristics. Comparison between the transmission values measured for the rabbit and human ocular media was found to be "remarkably similar". Percentage absorption of light incident on the retina and choroid was also compared and the spectral absorption characteristics of the human fundi found to be "strikingly similar to those of Chinchilla Grey rabbits exhibiting medium to dark pigmentation" (72).

More definitive data regarding species differences are needed. In addition, the effects of the shiny connective tissue layer, the tapetum lucidum, underlying the pigment layer of some experimental animals should be investigated. This reflecting layer causes some of the incident energy to traverse the pigment layer twice and may therefore increase absorption. Since the eyes of most nocturnal animals have a tapetum lucidum, this may represent an important factor in interpreting animal data from specie to specie or to humans.

6. Variations in Eye Structure and Dynamics

The normal relaxed eye brings all objects more than 20 feet distant into sharp focus on the retina. Uncorrected astigmatism, myopia, hypermyopia, or voluntary accommodation to focus on a closer point will cause the image produced by a distant light source to become larger and more diffuse or "fuzzy". Similarly, a more oblique angle of incidence prevents sharp retinal focusing since with increasing obliquity there is a proportional increase in astigmatism (71).

If the eye is focused on a nearby object, the light energy from a distant source will be focused at a point in front of the retina. The image on the retina will be larger, since it is out of focus, but a high concentration of energy will occur in the vitreous medium where focus occurs. For normal young eyes with high transmission, sufficient absorption may not occur to cause damage. However, for older people with reduced vitreous transmissivity, coagulation of the humor is a possibility. Pronounced changes in opacity of the ocular media with age have been reported (195), although much of the change is attributed to opacities of the lens.

The latency and duration of eye movements in the horizontal plane were investigated by White, Eason, and Bartlett (189). A latency of about 240 ms was observed and movement rates were found to vary with extent of movement, ranging from 7 ms/deg for 10^{o} movements to 3 ms/deg for 50^{o} movements. Westheimer (187) measured latency of the fixation reflex and reported a range of 120 to 180 ms. Gerathewohl and Strughold (75) reported that the latent period for onset of blinking or for eye movement in response to a high intensity flash averages 70 and 250 ms, respectively. The average duration of the blink reflex averaged 350 ms and movement time averaged 75 ms (for rotation of 11.5^{o}). Subjects tested averaged 22 years of age and had normal visual acuity. A study by deRivera and Webb (49) revealed that the eye can rotate at rates of 500^{o}/sec (2 ms/deg), but cannot smoothly track at rates over 25^{o}/sec. All of the above authors reported large individual differences between subjects.

For high altitude detonations, the development and duration of the thermal pulse may be 90% complete in a millisecond or so. For such conditions, eye movements would not play a significant role in altering effects. However, for atmospheric bursts with a yield of several KT or greater, rapid saccadic movements could result in protection of the retina from burn, or in the case of suprathreshold doses, produce an elongated burn track across the retina, or multiple burn sites corresponding to multiple fixations.

Experimental data based on studies with monkeys and rabbits during atmospheric nuclear test studies have indicated the potential importance of eye movements and short blink reflex periods to chorioretinal burn production (2). It was found that the light emission from large yield weapons, exploded at low altitude, was of sufficiently long duration that the blink reflex (less than 0.5 sec) could actually protect those animals that had blinked and kept their eyes closed, but those that immediately reopened, then blinked again several times, received multiple burns up to 3 sec after the detonation of megaton range weapons. The multiple burns traced a path across the retina and are indicative that the saccadic eye movements came into play. It is noteworthy that in these studies monkeys experienced more multiple burns than rabbits, which was attributed to the greater curiosity of the monkeys. That curiosity is a potent drive in primates (particularly man) has been obvious and a number of recent experimental studies on monkeys have shown strong behavioral effects of the curiosity drive (21).

Based on the results of the animal exposures, it was reported that "it appears that the probability of sustaining significant damage to the macular region may be relatively small" (2). However, of the 9 known cases of human chorioretinal burns from nuclear detonation viewing, 4 received central lesions (see section 3 of this chapter).

In addition to the factor of curiosity interacting with the blink reflex and saccadic movements, there are certain intrinsic characteristics of both slower eye movements and head movements which develop early in life that would tend to cause an observer to involuntarily look in the direction of a bright light flash peripheral to his visual field (55). The duration and latency of these responses are shorter than the duration of light emission from a high yield weapon exploded at low altitude and could therefore tend to increase the number of expected casualties and could also produce more severe and more multiple burns. Double dumbbell-shaped lesions on the retina have been found in monkeys when the weapon thermal delivery was protracted and eye movements (or possibly slight head movements) swept the image of the fireball over the retina (153). The tracks of multiple burns across the retinas of monkeys exposed to high yield atmospheric bursts were not consistently directed towards the fovea, but rather tended to be "located in the upper temporal quadrant and extended toward the macula and into the perifoveal area" (2). Whiteside (192) observed the first 100 ms of a nuclear fireball located 3^{o} laterally and reported that 5 sec were required to recover sufficient foveal adaptation to detect a low level (1.1 millilambert) visual target. Whiteside did report a well-defined after-image of the fireball which conceivably could be used as a cue for guiding eye movements towards or away from a long-duration fireball.

High frequency tremor of the eye during fixation has been measured by a number of investigators (see, for example, 52 and 92). Influence of this tremor on eye burn is not apt to be significant unless the image size on the retina is 0.05 mm or less. Since the amplitude of the tremor represents a sweep of only 3 to 4 microns on the retina, the increase in irradiated area will be insignificant for large images or for exposure durations which are short in comparison to the tremor sweep rate (20 ms per cycle). For fireballs observed at very long ranges where the fireball size approaches that of a point source, and where the effective retinal dose is delivered over a period of 10 to 20 ms or more, the high frequency tremor together with diffraction effects, chromatic aberration, and imperfections in the optical system of the eye will restrict the minimum size of the retinal image to an area greater than 8 to 20 microns in diameter (155, 187).

7. Age and Transmittance of the Ocular Media

In a recent study, Wolf (196) has documented the evidence for significant alterations in the ocular media of older people. Work of other investigators was cited which established that greater scatter and absorption take place than had previously been assumed. Wolf reported in a study on 200 patients between the ages of 5 and 85 years an abrupt increase in the magnitude of scotomatic glare was found above the age of 40. These changes were correlated with the well-known changes in the optical media that occur with aging (irregularities in the fibers of the lens, denser fibers in the vitreous, lenticular sclerosis, and changes in color of the ocular media). With increasing age, there is an additional yellowing and increased absorption of shorter wavelengths of light. Such changes would not only alter transmission but also change the distribution of wavelengths reaching the retina. Since for young healthy individuals the transmissivity is so high throughout the visible and near infrared portions of the spectrum, small changes in the absorption of light by the ocular media do not constitute a major factor in ascertaining burn threshold under ordinary circumstances. The additional protection provided from age 40 to 65 due to reduced transmissivity of the ocular media is small in comparison to the potential effects of pupil constriction, for example.

8. State of Pupillary Dilation as a Modifying Factor

Pupillary reflexes are relatively slow when compared with the rate of light production by nuclear devices (123). Should exposures occur at night when the pupil is in a state of maximal dilation, approximately 5 to 25 times as much light would enter the eye and be concentrated on the retina than would occur with the constricted pupil for the light adapted eye.

Extremes of pupil dilation or constriction which may be induced artificially are greater than those that would be observed in natural daylight or night environments. Thus, pupil diameters ranging from about 1.5 to 8 mm have been reported although a range of 3 to 6.5 mm is normally observed (162). Protection from chorioretinal burns or flashblindness by artificial miosis has been seriously proposed and an experimental evaluation carried out (133). The results indicated that "ciliary spasm secondary to pilocarpine miosis" and reduction in visual acuity were not major problems under conditions of partial dark adaptation.

9. Methods of Determining Thresholds for the Production of Chorioretinal Burns

A number of empirical measurements in which experimental animals actually viewed high altitude nuclear detonations have been used to confirm prediction models for burn thresholds (2, 7, 43a, 135, 153). Because of the large number of uncontrolled factors inherent in such field studies, it is hazardous to infer threshold values from such tests. Laboratory simulation of nuclear detonation thermal effects are generally used to develop prediction models and to confirm theoretically derived relationships. The burn sources vary from laboratory to laboratory and generally produce spectral characteristics which differ among themselves and which may differ from the spectral characteristics of a nuclear fireball. In the case of lasers, the light is monochromatic at a wavelength which depends upon the type of laser used.

A major advantage of the laser for thermal deposition studies in living tissues is the ability to achieve small image sizes, high power levels, and brief pulse duration (the use of Q switching with lasers produces pulses which are shorter by up to 3 orders of magnitude than the pulse duration delivered by a high altitude nuclear detonation). Thresholds determined for these very short pulses are not comparable to those from longer exposures but are useful in developing an understanding of the thermodynamics of the eye structures. Interestingly, the differences in threshold for producing burns by both xenon lamp photocoagulator and ruby laser, when similar pulse lengths were used, are remarkably small. Geeraets and Ham (74) reported a threshold value of 0.16 cal/cm^2 for a 175 μs pulse from a standard photocoagulator and a value of 0.17 cal/cm^2 for a 200 μs ruby laser pulse (image size was 0.76 mm). A high intensity carbon arc having a spectral distribution approximating a 5800°K black body has also been used to determine burn thresholds (86). It is assumed that as long as the spectrum produced by the experimental source compares favorably to that for the absorption spectrum of the black choroidal pigment, melanin, absorption will occur in the same tissue layers, the same mechanisms will be involved, and differences in threshold values will be relatively small for gross damage. Errors due to differences between spectral characteristics of burn sources can be minimized by computing threshold doses in terms of absorbed retinal dose, a procedure which has already been used to demonstrate equivalence of thresholds from three laboratories (11).

10. Biochemical Chorioretinal Lesions Not Detectable by Direct Observation

The usual criteria in the determination of thresholds have been the presence of gross pathological visible lesions (ophthalmoscopic observation) or post-exposure histopathological alterations. These were used primarily because of the ease of evaluating exposures by these criteria. However, there is considerable recent evidence (27a, 50, 74a, 97, 104, 119a, 120, 161) indicating that biochemical changes occur at even lower levels of irradiance and which may cause functional impairment of visual acuity, either permanent or transient. In the section of this report which reviews human exposures, a visual scotoma is apparent even though no lesion can be seen during ophthalmologic examination. Between the levels which produce reversible dazzle and those producing ophthalmoscopically visible lesions, functional irreversible impairment of photoreceptors can take place. Chan, Berry, and Geeraets (27a) studied the alterations of soluble retinal proteins due to thermal injury using a micro agar electrophoresis technique. The amount of altered protein was greater for long exposures (500 ms) than for short exposures (175 μs), and can be detected 2 mm from a lesion produced by an exposure 40% above threshold. The extent of the thermal injury and its relationship to pulse duration is compatible with the concept of heat conduction as a significant modifying factor in the production of chorioretinal burns. McNeer, Ghosh, Geeraets, and Guerry (119a) noted electroretinographic (ERG) changes with large image exposures 50% below threshold for visible burns. The energy level which produced the ERG changes was computed to be well above that needed to alter soluble retinal proteins. Geeraets, Burkhart, and Guerry (74a) reported that histological preparations did not show alterations with exposures below threshold for ophthalmoscopically visible lesions. However, impairment of enzyme activity (DPN diaphorase and succinic dehydrogenase) could be detected at levels 10 to 15% below threshold for visible lesions.

C. Production, Histopathology, Clinical Manifestations, and Symptomatology of Chorioretinal Burns

There exist a large number of clinical reports on eclipse retinitis or solar chorioretinal burning. These reports are pertinent to chorioretinal burns produced by atomic fireballs and, although quantitative aspects of exposure time and energy absorption at the retina are lacking, these cases provide a large number of clinical reports regarding the symptomatology and rate/degree of recovery of the human retina following the production of a thermal chorioretinal lesion.

1. Eclipse Retinitis (Sun Blindness, Solar Chorioretinitis)

The incidence of lesions caused by direct viewing of the sun is particularly great during an eclipse, and since the mechanisms involved may be the same for either viewing the sun or a nuclear detonation, one would expect similar histopathological and symptomalogical changes. The literature on solar retinitis is extensive, so the findings of a number of clinical reports have been summarized in the following paragraphs.

Patients report the rapid development of symptoms one to four hours after exposure, including sensations of "tearing", "smarting", "blurring", "clouding", and "dazzling". In more severe cases, loss of vision was pronounced but some improvement was noted in time. The symptoms described by some patients are similar to the subjective impairments of vision found in snow blindness. The majority of the clinical reports were based on examinations which occurred months after exposure, with derangements of vision and loss of visual acuity ranging from 20/30 to 20/200. Lesions observed on the macula vary from small, single holes burned in various shapes to large holes. A number of cases were found with double large holes or multiple small holes. The lesions in the macula were easily visible and had the characteristic appearance of a deep crimson crater, irregular in shape with sharply defined edges and usually surrounded by a soft cloud of pigment. According to Agarwal and Malik (1), the severity of the lesion varied with the amount of energy absorbed and such lesions may be classified into four grades based on ophthalmoscopic changes:

(1) loss in acuity, macula apparently normal
(2) macula congested and surrounded by edematous area of retina
(3) a grayish-white patch surrounding the fovea which, in turn, was ringed by black pigment
(4) a macular hole and gross pigmentary change.

The 56 human subjects in this report experienced a variety of symptoms including one or more of the following: metamorphopsia, disturbances in color vision, translucid scotoma, photophobia, and persistent after-images(1). In the severe burns, absolute and positive scotoma developed with a gross diminution of vision. The basic pathological defect was considered to be similar to angiospastic retinopathy (i.e., vasospasm causing dimunition of retinal nutrition leading to localized ischaemia which, in turn, could bring about degenerative changes).

Treatment is briefly described in a number of the solar retinitis papers but, in general, the value of these clinical reports is to be found in the gross descriptions of the burns, symptomatology, and long-term alerations seen months or years later. Most subjects noted some visual recovery several days to several months later, but permanent losses in visual acuity were always associated with macular burns. Some patients learned to compensate for this defect by training themselves to utilize the undamaged portions of the retina (1, 26, 36, 37, 44, 52, 60, 67, 101, 113, 160).

2. Photocoagulation by Optical Devices (Photocoagulators, Lasers)

Another source for examining effects of intense concentrated light on the human retina comes from studies utilizing a photocoagulator to treat human patients for detached retina and other superficial abnormalities of the retina. The earlier work in this area has been reviewed by Myer-Schwickerath (130).

Curtin and Norton (43) reported on the histological effects of suprathreshold treatement with the Zeiss photocoagulator. Early pathological changes seen in the area of photocoagulation revealed extensive coagulation necrosis in all retinal layers and choroid, with the sclera being unaffected. The most extensive damage was found in the pigmented epithelial layer, and choroidal vessels were engorged with intravascular thrombo-emboli. The endothelial cells of the choriocapillaries showed necrosis, as did the walls of other larger blood vessels. Subretinal fluid shifts caused dissection of the sensory retina from the pigment epithelium peripheral to the site of burn (adjacent to focal spot). Disruption and scattering of the pigment was seen and necrotic changes were apparent in the rod and cone layer, the outer nuclear layer, and the outer plexiform layer. Choroidal vessels were dilated and engorged and a few inflammatory cells were scattered in the vascular layer. With more intense exposures, retinal rupture, hemorrhage, damage to the intimal limiting membrane, and leakage of subretinal fluid into the vitreous cavity were seen. By comparison with burns produced by direct viewing of the sun, the high energy photocoagulator lesions produced far more mechanical disruption of all retinal tissues.

Recently, Geeraets and Ham (74) reviewed the retinal effects of laser irradiation. They reported gross disruptions of the retina with both laser and photocoagulator high energy pulses to an area 0.76 mm in diameter on the retina. Retinal elements were forced out into the vitreous but no changes were seen in the subretinal tissues. Lesions were not uniform and hot spots in the same eye were seen, these hot spots being attributed to local differences in degree of pigmentation. Histologically, some areas developed more intense damage than others, but major effects were found in the pigment epithelial layer and in the receptor cells. Depending on the intensity of the lesion, the tissue responses varied. In moderate lesions, loosening of the retinal receptor cell layer from the pigment cell layer was common. This change was even seen in mild lesions, but with increasing intensity of heat input the lesion appears to have actually erupted. Subretinal hemorrhage and dispersion of pigment cells into the vitreous through tears in the retina were found. (In the area of the lesion, lipoidal globules were observed. *)

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*Pathological significance of appearance of lipoidal globules has not been established.

Zaret (200) has described experiments where, as laser energy input was increased, vaporization due to intense heating caused an explosion of the retina and marked dispersion of pigment granules. Three days post-irradiation, Zaret noted a central zone of destruction surrounded by a gray exudate and peripherally, a halo of pigment. Four to fourteen days later, hemorrhagic material began to disappear, and by thirty days scarring and some recovery were noted. Zweng and Flocks (202) using a modified hand-held laser photocoagulator reported almost instantaneous development of retinal hemorrhage following lasing. The lesion had a characteristic central red spot (bleeding) circumscribed by a halo which contained vapor bubbles up to 15 minutes post-exposure. Tears in the retina and dislocation of pigment were seen near the macular hole. Subsequently, scar formation took place, edema subsided, and circulation was restored, leaving a scar surrounded by a halo of atrophic retinal tissue.

Ham and his co-workers (84, 85, 86) have compiled probably the most abundant controlled data on chorioretinal burns in experimental animals. In addition to previously cited effects, they noted an almost immediate swelling of the nerve fiber layers and marked pyknosis of all nuclei in the inner and outer layer. The neurons of the ganglion cell layer were completely structureless and structure of rods and cones in the burnt area was lost. The pigment epithelium showed marked pyknosis, fragmentation, and chromatolysis. The choroid showed little change immediately post-burn. However, three days later, marked choroidal hyperemia was seen with relatively little leukocytic infiltration at that time. The subsequent histological alterations were similar to those described earlier in this review.

The studies of DeMott and Davis (47, 48) give a good description of some of the responses seen in chorioretinal burns. Immediately post-trauma (5-30 minutes), visible lesions consisted of intrusions of fluid into the sclera, choroid, and retina. Intrusions were most often observed between the receptor and bipolar cell layers of the retina. From 5 to 36 days post-trauma, the fluid intrusions gradually coagulated and shrank, with resorption of the clot completed by the end of this period. Necrosis of retina appeared in the center of the lesion and there was retinal detachment. In some of the less severe cases, there was a tendency for the retina to re-attach in the healing process. However, in those cases where the intrusion is between the receptor and bipolar layers, the functional loss should be permanent. As intensity of irradiance increased, it was noted that pigment cells and retinal elements were immediately destroyed. At even higher intensities, bipolar and ganglion cell layers were destroyed. Even if not directly involved, these latter cells will show a secondary degeneration if the receptors they synapse with are destroyed. Such retrograde degeneration would in all probability eventually be seen through the entire CNS optical projection involving these receptors and neurons. In summary, DeMott and Davis (48) found that near-threshold lesions could take three forms:

(a) circumscribed retinal detachment, possibly temporary,

(b) separation of bipolar and retinal cells leading to retinal degeneration, or

(c) direct destruction of retinal and neural elements.

They estimated 95% of all threshold lesions would fall in the latter two categories.

3. Case Histories of Damage to the Human Visual System, Nuclear Detonation

There are nine recorded cases of human chorioretinal burns which resulted from viewing a nuclear fireball--directly or indirectly. Occurrences such as these have provided valuable information for correlating human with animal data on threshold levels, symptomatology, and effects on vision. Unfortunately, difficulties in reconstructing the field exposure conditions have restricted the accuracy with which threshold interpretations can be made.

Case 1

The first recorded case was a Japanese survivor of the Hiroshima atomic detonation (31). This person sustained bilateral central lesions. However, irradiance and duration of exposure have not been determined. The greatest value in this particular recorded case (where thousands of survivors were examined) is an indication of the low probability of retinal burn among survivors under the specified conditions at Hiroshima. (That is, constricted day-time pupil, city location where buildings offered many shadows, air burst, low-yield weapon, etc.)

The next body of information on retinal burns was published in 1957 (22). Here, six test personnel were affected who were located at various distances from low altitude or surface detonations. By reviewing the yields for weapons detonated up to 1956 in Effects of Nuclear Weapons (78) and noting the distances from detonation (2 to 10 miles) that cases were listed for, it is inferred that the yields were less than 50 KT. It was reported (42) that five of these six cases were not using the recommended eye filters (one of the victims was using a 3% filter). The thermal irradiance values have not been published for these cases so little can be extrapolated about burn thresholds.

Case 2

A photographer viewed the latter part of the fireball through a camera optical viewfinder while flying six miles from the detonation. The left eye was viewing through the camera, the right eye was exposed unshielded. Immediately after detonation, there was a marked dazzle effect followed later by blurring, haziness, photophobia, and "shimmering". These effects persisted sufficiently to prevent the photographer from driving an automobile hours later. Twenty-four hours after exposure, visual acuity was 20/30 O. D. and 20/50 O. S. The eyelids were swollen and conjunctivae were injected. In 48 hours, acuity had increased to 20/15 O. D. Ophthalmologic examination showed the right fundus to be normal, while foveal reflex was minimally diminished in the left eye. A broad, diffuse relative scotoma was noted in the left nasal paracentral area, but no lesion could be seen.

Case 3

A pilot, located five miles from the detonation, viewed the fireball through an aircraft window, right eye only. The case report states that the pilot was blinded for 15 sec and had only limited vision of instruments for the next 10 sec. It is not stated if this blindness refers only to the affected eye, or was apparent in both eyes despite the fact that the left eye had been covered.

The hazy vision persisted for about 10 minutes. Seven months later, acuity was 20/15 in each eye. A paracentral 2^o absolute scotoma was noted in the upper temporal quadrant, surrounded by a 5^o relative scotoma, but no lesion was detectable ophthalmoscopically.

Case 4

Another pilot, 10 miles distant from a fireball, commenced observation 50 ms after detonation.* Viewing was with the left eye only, no protective filter. Subjective visual difficulties lasted for about 5 minutes. Five days after exposure, acuity was 20/15 each eye; identical to acuity before the nuclear test. A 2^o scotoma was located proximal to the fovea. Interestingly, the lesion occurred on or near a retinal artery, and it was observed that blood flow had been diminished in that artery distal to the lesion. The blanched area was still edematous after 12 days, but one month after exposure the retinal edema had disappeared.

Case 5

An airman, located 10 miles from detonation point, viewed the fireball with both eyes unprotected. He immediately blinked and turned away and did not note any subjective symptoms. Bilateral 5^o lesions were discovered two

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*It is not clear how this exact time interval was determined.

months later. The lesions were oval, slightly depigmented along the edges, and located between 5° and 10° from the macula. Visual acuity was 20/25 in each eye. No changes were noted in the succeeding 18 months.

Case 6

An officer, 7 miles from the detonation point, viewed the fireball with one eye. The right eye was covered and the left eye was protected with a 3% transmission filter. Immediately after exposure, the officer noted a central blind spot in his left eye. A 4° paracentral scotoma was mapped. Ophthalmoscopic examination revealed a lesion with elevated yellowish-pink margins and visible gray sclera showing through the center. No hemorrhage was observed, although the area around the lesion was slightly edematous. Three months later the scotoma and lesion remained as before. After one month, acuity was 20/20 corrected, each eye.

Case 7

An officer 2 miles from a detonation point viewed the fireball with his left eye only. Just after exposure, acuity for the exposed eye dropped to 20/200. Six weeks later acuity was 20/70. The scotoma was located centrally and extended 5° by 8°. Ophthalmoscopic examination of the lesion showed tension lines radiating out from the lesion, which could indicate the possibility of future retinal detachment. The lesion was surrounded by an edematous area and was itself of a "brownish color with a pigmented spot in the center".

There are several important aspects of these test personnel case histories. First, only two of the six lesions involved the fovea although all of the individuals "viewed" the fireball. This may indicate a delay factor in foveal fixation. Whether the initial, parafoveal, intense stimulation has an aversive quality which tends to inhibit foveal fixation can only be speculated. Such a reflex effect would only be of significance for detonations which persisted for periods approaching a second or more. Second, these cases illustrate the necessity for making a distinction between presence of functional impairment and absence or presence of visible lesions. In Case 2, for example, a large scotoma was mapped without ophthalmoscopic evidence of a lesion immediately after exposure. Case 3 showed both relative and absolute scotomas, but no visible lesion when examined 7 months later. Conversely, distinct lesions have been noted close to the macula, but foveal acuity has returned to normal when the edema subsided and the lesions became stabilized. Third, in two of the above cases the lesion occurred on or near a blood vessel and vascular changes were noted in the vicinity of the damage. Pertinent to this observation, there is an interesting question about the rate and extent of repair of a retinal area (secondary damage) as a function of the vascular state. That is, the retinal vessels in patients with diabetes, high blood pressure, atherosclerosis, etc., would not be expected to respond as well to traumatic lesions as would normal vessels.

Cases 8 and 9 occurred during the 1962 Fish Bowl Series (3). The particular detonation which produced the injuries was a very high altitude night shot. The burns were sustained at a slant range of about 30 miles. Neither individual had his protective goggles on during the detonation. The pulse characteristics of this particular detonation were such that the peak irradiance was achieved in a small fraction of a millisecond, and had trailed off to low levels well before a blink reflex could occur. Peak irradiance (3) at the ground station was between 2 and 3 watts/cm^2. This means that the blink reflex would have been of no protective value and that the injured individuals had to be fixating at the exact detonation point when the detonation occurred. One case does give evidence which suggests that the eyeball may have been in motion during the damaging phase of the fireball, since a small tail-like extension was observed on the lesion (3). However, there is also a remote possibility that the two burn victims could have been burned by a specular reflection rather than the direct image. Such reflections could occur from a wristwatch face or any of a variety of shiny metal or glass surfaces.

The clinical data for these latter two burn cases is fairly typical except that the damage to central vision was more pronounced than the six cases cited previously. In the first case, acuity for central vision was 20/400 initially, but returned to 20/25 by six months. The second victim was less fortunate as central vision did not improve beyond 20/60. The lesion diameters were 0.35 and 0.50 mm, respectively. Both individuals noted immediate visual disturbances but neither was incapacitated. In a recent review (42) of these two cases, the fact that chorioretinal burns on or near the fovea do not necessarily cause complete blindness was emphasized. Both <u>size</u> and <u>location</u> of the lesion determine visual impairment.

The functional significance of permanent retinal damage is dependent upon two, and possibly three factors: the size of the lesion, the location of the lesion, and subsequent physiological secondary reactions around the lesion site. The first two points are obvious and will be expanded upon below. However, the third factor is one about which little factual information is available. The question here is: will there be delayed or progressive deleterious effects on vision following subsidence of the initial inflammatory reaction after receipt of a chorioretinal burn? In one of the cases of human retinal burns (159), the examining physicians note the appearance of tension lines around the lesion, and suggested that this could indicate the possibility of future retinal detachment. Similarly, Geeraets noted* having seen, in experimental animals, stress or tension lines in the vitreous humor following retinal burns. Whether these isolated examples are indicative of a complication not previously expected will remain to be confirmed by long-term observations.

Returning to the significance of the size and location of retinal lesions, the lesions seen in the accidental human exposures have all been found on or near the fovea. Burns directly on the fovea produce reductions in acuity,

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*Personal communication.

the extent depending upon the lesion area. For example, it was calculated, considering only the theoretical geometry of the human eye and measures of relative acuity in peripheral fields of the retina, that a lesion covering 2.5° (1.25° on each side of the fovea) would reduce acuity to 57% of normal, or 20/35. If the lesion covered 20°, acuity would only be 15% of normal, or 20/130 (43a). The fact that the theoretical residual acuity is not always obtained (Case 9, for example) may indicate that the damaged area exceeds the area of the visible lesion, or that some individuals have difficulty learning to "look around" a central scotoma.

Burns located off the fovea will produce blind spots, which subjectively may not be apparent to the individual. However, the visual defect resulting from a parafoveal lesion may not be confined to the lesion area, depending upon the types of cells which are involved. If damage is confined to receptors (mostly rods), the blind spot will be at the lesion site. If nerve fibers are damaged, that portion of the visual field served by those fibers will show a defect. As the axons progress from the periphery of the retina to the optic disc, they form symmetrical bundles. The only exception to the symmetry of these radial fibers and bundles occurs between the macula and the disc. These fiber bundles leaving the fovea are more delicate (154), and therefore, their thermal damage threshold may be lower than the threshold for extra-foveal axon bundles. However, because of the construction and nonpigmented character of nerve fibers, their exposure threshold should be considerably higher than for receptor cells and the pigmented retina. This value is not known.

In the literature reviewed for this report, no description of burns on the optic disc were found. If a burn did occur on the disc, it could cause direct damage to large groups of axons or to retinal blood vessels. Hemorrhage from ruptured vessels could increase ocular pressure, obscure vision by loosing formed elements into the vitreous, and cause neural anoxia distal to the lesion site. There would seem to be a low probability that the fireball image would fall upon the disc since the individual normally does not focus objects in that location. Also, the absorption of light energy is less for these tissues. It might be worthwhile, however, to examine this question experimentally, if for no other reason than to reassure the investigator that optic disc burns are improbable and/or difficult to inflict.

One of the most significant conclusions derived from observations of the accidental human retinal burn cases is the fact that even with foveal lesions, the individual eventually regains a good portion of his visual acuity (42, 159). Probably the eye scanning patterns are changed slightly to bring objects to focus on undamaged portions of the fovea. On the other hand, the immediate sensations of visual disturbances reported by individuals who have sustained retinal lesions would impede the performance of all but gross visual tasks.

In summary then, the individual sustaining a retinal burn may be effectively visually incapacitated for an hour or more. Barring possible long-term effects, such as retinal detachment or contractions of the vitreous, the visual field defect will eventually subside to an area about the size of the original burn. One of the pressing questions concerns the problem of explaining the mechanism of damage where there is a scotoma without a visible lesion. Are alterations in retinal proteins or enzyme activity responsible, and can this condition be reversed?

D. Mechanisms Involved in the Absorption, Transformation, and Dissipation of Energy

1. Steam Production, Shock Waves, and Mechanical Disruption

Injury mechanisms for suprathreshold doses are believed to differ from those for near threshold doses. If the rate of energy delivery is sufficiently high, such as may readily be obtained with lasers, tissues may be heated sufficiently to vaporize intracellular and extracellular fluids.

Such sudden vaporization would produce high pressures and mechanical disruption of surrounding tissues. Mendelson (124) exposed excised human tissue and gelatin models to short intense laser pulses and was able to produce: (1) supersonic shock waves, (2) acoustic waves (3) mechanical waves (less than the speed of sound), and (4) secondary pressures in a closed compartment whose effects were both dynamic and hydrodynamic. The shorter the pulse duration and the greater the energy input, the greater the shock wave production. In a water phantom, shock waves were recorded at peak pressures over 1000 psi and it is estimated that in tissue the peak pressure might be twice as large. In the gelatin models, shock waves of over 2000 psi were recorded and in thin sections of monkey skin 5000 psi pressures were found following a single high intensity short duration laser pulse. However, the pressure waves were rapidly attenuated and resulting effects restricted to a localized area.

Minton (134) has photographed the explosion of tumor tissue following laser irradiation. High speed motion pictures show the development of shock waves and dramatic eruption of the irradiated site. Zaret (200) has reported that with suprathreshold energies from lasers, vaporization and implosion of the retina, with dispersion of pigment granules, may occur. Zweng and Flocks (202) reported that gas bubbles have been observed to persist up to 15 minutes after intense irradiation, and that fractures or tears in the retina immediately after irradiation attest to the mechanical forces which occurred. Vos (185) has expanded the critical temperature concept (85) to include steam production as a significant consideration in retinal burn production. In Vos' theoretical model, high rates of delivery of large amounts of energy tend to favor steam production over coagulation as the major source of damage.

Experimental work with suprathreshold exposures sufficient to produce steam and mechanical effects requires an unusually intense energy source. For this reason lasers have generally been used whose pulse characteristics differ in several respects from those of a nuclear fireball. Steam production and mechanical disruption have not been documented for either the animal or human chorioretinal burns resulting from exposure to nuclear detonations. However, observation of a high altitude burst through a telescope or other light gathering device could result in equivalent rates of energy delivery.

2. Effects of Temperature

At temperature in excess of 100°C all proteins coagulate and at temperatures below this, many proteins, nucleic acids, and biologically active, smaller molecules are structurally altered with subsequent alterations in cellular and tissue function. According to Vos (185) some proteins coagulate between 45° and 60°C and that at still lower temperatures an increase of only a few degrees might produce temporary functional impairment by direct molecular production of excessive metabolic waste products. For example, increase of only 4°C testicular temperature produces changes in viability of gametes. A complete review of thermally damaged tissue is beyond the scope of the present report; however the fact that cellular changes do take place suggests that low level increases in temperature may alter nucleic acid structures and function. Such alterations would be difficult to assay by standard clinical or histopathological techniques but might nevertheless disrupt function.

Vos (185), Ham et al.(85), Jacobson et al (100), and others have attempted to analyze the thermal alterations in the eye following chorioretinal burning. There is evidence to suggest that local circulation characteristics are such that blood flow would not play a significant role in the dissipation of short pulses of thermal energy. However, it has been suggested that the vitreous humour may play a major heat dissipation role. Wray (198) developed a "heat generation" model of the retina used in a computer program for predicting chorioretinal burns. Thermal properties of the tissue were assumed to be nearly the same as water. Transmission through the pre-retinal ocular media and absorption in the pigment epithelium and choroid were computed using coefficient values reported by Geeraets, et al. (72). The thickness of the pigment epithelium was taken as 10μ and the choroid as 80 to 100 μ. Wave length bandwidths for coefficients were taken as 10 mμ over the range from 350 mμ to 1500 mμ. The spatial and time varying temperature profiles in the volume of tissues are computed for specific weapon and environment characteristics. Wray suggests that a temperature rise of less than 20°C for a second or less is unlikely to cause irreparable damage, while a 65°C increase will undoubtedly produce permanent damage.

Ham, Williams, Mueller, et al. (83 b) have emphasized the necessity for an accurate time-temperature history before trying to describe the chemical kinetics of thermal damage. The authors cite unpublished computations by Schmidt at the Medical College of Virginia which describe transient retinal temperatures in the pigment epithelium with threshold exposures for minimal visible injury. Schmidt used an electrical analog model to simulate the effects of conduction on transient temperature. The maximum temperatures computed vary slightly with exposure time for pulses from 20 ms down to 200 μs (a range of 46.8 to 55.0°C increase above ambient). A markedly lower maximum temperature was computed for pulse durations of 30 nanoseconds, probably due to selective absorption of photons in the pigment granules and negligible heat flow to the surrounding tissue during the pulse. Ham, et al. attribute the mild retinal lesions produced by exposure durations of 175 μs or more to thermal damage in the pigment epithelium. The differential equation of heat flow applied to "relatively crude physical models which approximate conditions in the ocular fundus" adequately explain the gross phenomena associated with the production of such lesions.

3. Relationship Between Image Size and Rate of Exposure in Production of Elevated Temperature

Jacobson, et al. (100) reported that the "dose required to produce a specific burn increases with the degree of burning". This is of course difficult to evaluate for burns less than 1 mm in diameter and may be the source of some inconsistencies among reported burn thresholds. The authors also reported that the burn threshold dose increases with increasing retinal image size (range 0.7 mm. diameter to 4.0 mm. diameter). Ham, et al. (85) found an inverse relation between the burn threshold and retinal image size, but their range of image sizes (0.18 mm. to 1.1 mm.) only just overlapped the smallest of those used by Jacobson, et al. (100). Both groups agree that the integrated threshold dose increases with decreasing irradiance (a departure from reciprocity*) but that this effect is not as marked with large images as with small ones. Bredemeyer, et al. (11) prepared families of absorbed retinal dose threshold curves based on their own data as well as on the work of Ham, et al. (85) and Jacobson, et al. (100). For images producing burns of 1 mm or less in diameter, all three sets of data are in good agreement. The findings of Jacobson and co-workers for burns greater than 1 mm have yet to be confirmed by other investigators and such confirmation may be desirable. According to Ham the departure from reciprocity is due to an increased efficiency of conduction of heat by the surrounding tissues as image dimensions decrease (increased surface to volume ratio) assuming that cooling takes place mainly along the retina. Jacobson suggests that if this were the case the lesion should have a fuzzy margin and that the lesions they observed are well defined. This difference in opinion is difficult to reconcile. Jacobson did make some thermocouple measurements and reported that the temperature was raised

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*A curve representing true reciprocity would be represented by a hyperbola, threshold = kH_rt, where k is a constant for a given image size, H_r is the retinal irradiance, and t is time.

less than 0.1°C, 1 to 2 mm. from the central image which was 20°C above body temperature (note, however, that the volume of a 5 mm. diameter sphere is 125 times that of a 1 mm sphere).

Major emphasis of past research has been devoted to defining threshold conditions for producing visible lesions. Much research remains to be done in the definition of the effects of both suprathreshold doses, and doses which produce functional effects without visible evidence of damage.

E. Enzymatic Photo-Alterations Related to Possible Biochemical Lesion

Researchers using lasers on a variety of enzyme solutions in vitro have reported little or no effects, except for the moderate inactivation of peroxidase (97). The selective sensitivity of peroxidase may be related to the observation of long-lived organic free radicals in the skin of mice exposed to laser irradiation (50). Usually, free radical production is also accompanied by the production of peroxides which may have cytotoxic effects. If peroxidase is selectively destroyed, peroxides will not be broken down as quickly as usual and could be another source of biological effects from very intense thermal energy on the retina. However, compared to the damage inflicted by temperature and steam-produced mechanical disruptions, the effects of free radicals (if any) would probably be inconsequential. It should also be pointed out that biochemical alterations to any moiety except DNA are usually reparable.

F. Physiological Factors Which May Modify Threshold

In the following sections, clinical and experimental evidence describing secondary inflammatory responses will be briefly summarized, as well as information regarding known or hypothesized mechanisms.

Once damage threshold levels are determined by experimentation and realistic criteria have been set for eye protection systems, attention is then turned to the question of mechanisms of action. Eventually, it is hoped that a means can be found to develop therapeutic techniques which will lessen the severity of retinal damage. Little can be done for portions of the retina where neural elements have been destroyed, but there is a possibility that means can be found to accelerate the repair of adjacent tissues and thus minimize the area of visual impairment.

Due to the small lesion size and poor accessibility the study of retinal lesion pathophysiology is difficult. To date, one approach has seen to inflict the lesion, excise the eye at various post-burn intervals, and then analyze the biochemical activity at the borders of the lesion (74a). Another approach is to study thermal effects on more accessible non-retinal tissues (such as the hamster cheek pouch), and project these findings to the retina.

Transient Effects

It has long been recognized that damaged tissues and necrotic areas release a variety of biogenic materials which in turn have a pronounced transient effect on adjacent normal cells. This effect may be seen in the cases of human chorioretinal burns where partial recovery of vision occurs in several days or weeks.

Schulman, et al. (166), studying the effects of uniform burns on the hamster cheek pouch note marked neovascularization and vasodilation around the burn. By 200 hours post-burn, repair appears to be complete and the blood vessels are normal. Administration of corticosteroids reduces the degree of secondary effects.

Fulton (66) and Geeraets, et al. (32) have studied the microcirculation of areas adjacent to trauma sites, both observing vascular effects as vascular stasis, adhesiveness of formed elements, and eventual recanalization.

Biogenic amines such as heparin, histamine, and serotonin are released from mast cells under some conditions of trauma (66, 149). It is speculated that these amines may produce a transient disruption of retinal function adjacent to a burn site.

Chan, et al. (27a) have examined the activity of soluble retinal proteins adjacent to a burn site, using micro agar electrophoresis. This technique has permitted a quantitative and qualitative analysis of the tissues concentric to the burn. A relationship is shown between the duration of exposure and loss of soluble protein, and this relationship as a function of distance.

The role of stress, via adrenocortical activity, may also have an effect upon secondary responses surrounding the burn site. Elevations in aldosterone secretion could enhance the duration of post-burn edema, because of greater fluid retention within tissues. Also, decreased amounts of steroids responsible for reduction of inflammation could contribute to prolonging the duration and extent of inflammation around the burn. Fulton's studies (66) on the effect of steroids in lessening the degree of secondary inflammation might serve as an appropriate example.

G. Models for Predicting Chorioretinal Burns

A number of models have been developed for predicting chorioretinal burns, or temperature-time profiles, from exposure to nuclear weapon detonations. These models differ among themselves as to techniques for deriving weapon emission characteristics, atmospheric attenuation, pre-retinal ocular attenuation, absorption in the retina, and for interpretation of the consequences. Problems in defining weapon emission characteristics were discussed in Chapter IV. Problems and techniques for computing atmospheric transmission were also described in Chapter IV. The models for predicting burns from such data are described in the following paragraphs.

Ham, et al. (86), combined equations for thermal energy incident on the cornea and for retinal-image-concentrating effects, to arrive at the following formula for "the total or integral retinal dose Q_r" as a function of range:

$$Q_r \ (\text{cal/cm}^2) = \frac{E \exp(-\alpha D)}{4 AR^2}$$

where

$$A = \frac{4\pi(\text{focal length in cm})^2}{0.80\ d^2}$$

E	=	total thermal yield in calories.
α	=	mean attenuation coefficient of the atmosphere (same units as D)
R	=	radius of the fireball (cm)
d	=	pupil diameter (cm)
D	=	range (same units as α)

Transmission through the ocular media was taken as 0.80 (described as the average transmission coefficient of the rabbit eye for radiation from a 5,800°K source). Plots of Q_r for the rabbit and man as a function of slant range for several weapon sizes are included in the report. Pupillary diameter of 0.8 and α of 0.1 km^{-1} were used. The authors cautioned that differences in atmospheric transmission, pupil diameter, and blink time have a profound influence on thermal dose. However, when all factors were considered, the retinal hazard on the ground was not regarded as appreciable for low altitude bursts, "except for personnel using optical instruments or performing observational duties at night". Evaluation of the consequences of Q_r was made in terms of the threshold exposure for producing minimal lesions on the rabbit retina in the laboratory with 150 ms pulses and an equivalent retinal image size.

Wray (197) developed a generalized mathematical method of calculating radiant exposure of the retina from high altitude bursts. Wray emphasized "that the accuracy of the predictions rests in properly defining the amount of radiant energy, making a reasonable calculation of atmospheric attenuation, and estimating the size of the radiating fireball". The equations used by Wray for showing the relationships between fireball size, yield, atmospheric transmission, pupil size, and retinal irradiance were similar to those which appeared in the article by Ham, et al. (86), and in the 1957 ENW. However, the method of computing the values for several of the parameters was different for the high altitude situation. The following parameters were used: two-thirds of the yield was assumed to be thermal radiation, all radiation was emitted in the first 50 ms, fireball size was scaled from measurements of shot TEAK using yield to the 0.4 power and atmospheric density to the -0.1 power, and atmospheric visibility was greater than 50 miles. Evaluation of burn/no-burn conditions were made by comparison with the rabbit threshold data reported by Ham, et al. (86). However, Wray cautioned that the available threshold data was limited for application to the high altitude problem and that further extension of laboratory experiments to smaller image size, higher irradiances, and shorter exposures was needed.

Smith (172) computed retinal exposure versus distance and yield for several atmospheric conditions using the equation:

$$Q_r = \frac{d^2}{(\text{focal length})^2} \int_{t_1}^{t_2} \int_{\lambda_1}^{\lambda_2} f(\lambda)\,\phi(\lambda)\, E\, d\lambda\, dt$$

where d = pupil diameter

t_1 = initial time

t_2 = blink time (0.1 or 0.3 second)

λ_1 and λ_2 are 380 mμ to 1,800 mμ

E_λ = energy at each wavelength emitted per unit area of the fireball (computed from the temperature-time curve for a 20 KT burst)

$f(\lambda)$ = fraction of energy transmitted without scattering through the atmosphere (obtained from published measurements for various atmospheric conditions and distances)

$\phi(\lambda)$ = pre-retinal ocular transmittance

For weapons from 1 KT to 1 MT, the time scale of the fireball temperature-time curve was varied as yield to the 0.5 power. The evaluation of exposure was made in terms of maximum range for the production of: (a) shallow retinal burn (25 μ depth), and (b) serious retinal burn (150 μ depth). Doses required to produce shallow and deep burns were based on an earlier theoretical analysis by Smith which he reported showed "fairly good agreement with the experimental results obtained by Ham (86) working with rabbits". Maximum ranges were given in tabular form for 0.1 second and 0.3 second exposures, with pupil sizes of 4 mm and 8 mm, with visibility measures of 2, 5, and 20 miles, and for observers whose line of sight is directed towards the burst, at 60°, or at 80° from the burst.

Pickering, et al. (153), presented equations for computing retinal irradiance which included a more sophisticated analysis of atmospheric transmission (see Chapter IV):

$$Q_r = \frac{a\, f\, p\, T_E\, r_p^2\, W \times 10^{12}}{4 \pi F^2\, r_{fb}^2} \exp(-k\, I).$$

where a = spectral-attenuation factor (0.5)

f = fraction of total thermal energy emitted during blink reflex

p = fractional thermal partition

T_E	=	fractional transmission of eye system
r_p	=	radius of pupil (cm)
W	=	yield (KT)
F	=	focal length of eye
r_{fb}	=	radius of fireball (cm)
k	=	air attenuation coefficient (cm^2/gm)
I	=	integrated air density over the optical path (see original reference for computation techniques for observer at surface or at altitude)

The consequences of a given retinal irradiance were evaluated in terms of thresholds for minimal lesions in the rabbit as reported by Ham, et al. (86). Estimated fireball image diameter and computed radiant exposure accurately predicted burns at all stations where burns were received during shot TEAK and at all stations where line of sight was unobstructed during shot ORANGE. The sizes of the observed retinal lesions varied inversely with the slant range, but were approximately 2.6 times greater in diameter than the estimated image size.

Rose (159a) described a method for calculating the temperature response of the human retina from weapon yield, atmosphere, eye pigmentation, and observer altitude. The method utilizes a computer program to calculate a "transient temperature history for each element in the thermal model". Equations for computing retinal image size using given values of fireball radius are specified. Irradiance on the retinal image is computed by correcting calorimeter irradiance for the concentrating power of the eye and for the various atmospheric and ocular attenuation factors (see Chapter IV for a description of atmospheric attenuation). Absorption in the retina and choroid are assumed to follow an exponential law and require knowledge of attenuation coefficient and path length through each layer. A thermal network is then used to solve for heat transfer and temperature at each of up to 100 nodes in the irradiated area.

Wray (198, 199) prepared a computer program for predicting chorio-retinal burns from nuclear weapon explosions. The program computes "spatial and time varying temperature profiles in the energy absorbing layers of the eye tissues". Thermal energy production is computed by assuming black-body radiation and typical temperature, and radii as a function of time for a 1 KT sea level explosion. Scaling to other yields is accomplished by use of the ENW scaling laws (see Chapter IV). Atmospheric transmission computation techniques used by Wary have been previously described (Chapter IV). Pre-retinal attenuation in the ocular media is computed by using the measured values reported by Geeraets, et al. (72). Absorption in the pigmented epithelium and choroid are also computed as a function of wavelength using values reported by Geeraets and co-workers. The pigmented epithelium was assumed to be 10μ thick and the choroid $80-100\mu$ thick. If the computed image radius was less than 3.5μ, a correction factor was applied. Absorption and conduction were assumed to occur uniformly and all tissue thermal properties were assumed to be nearly the same as water. The fundamental heat conduction equation was then put into difference equation form and used to compute "the temperature rise above the ambient body temperature". A temperature rise of $20^{\circ}C$ for a time period of the order of the blink reflex was specified as an interim damage criterion until better laboratory data are available.

Allen, et al. (2), included graphs of representative temperature distributions in the retina and choroid as a function of time distance from the center of the image. These distributions were computed using Wray's (198, 199) program. Allen also described an "approximation model" for computing effective radiant exposure at the retinal image Q_r^{eff}. Up to blink time (t_b) the following equation is used to compute effective radiant exposure:

$$Q_r^{eff}(t_b) = \frac{a\, p\, b\, (t_b)\, W \times 10^{12}}{(2\, f)^2\, 4\pi r^2(t_b)} \, \overline{T}_{at}(M, W)\, \overline{T}_x\, \overline{T}_e \quad cal/cm^2$$

where a = fraction of the total thermal energy which is effective in producing retinal damage

p = thermal partition

$b(t_b)$= fraction of thermal energy released before blink

W = yield in KT

f = effective focal length of eye divided by pupil diameter

$r(t_b)$= radius of fireball at t_b

$\overline{T}_{at}(M, W)$= average atmospheric transmission in the path

$\overline{T}_x$ = average transmission of intervening material such as windows, etc.

$\overline{T}_e$ = average transmission of clear ocular media

Thresholds for radiant exposure for irreversible damage reported by Ham, et al. (86) are used to evaluate the threshold distances at which observable retinal damage will be produced.

Allen, et al. (3a), used the approximation model to compute retinal irradiances during a recent test series. Burns predicted on the basis of calculated exposures were observed, whereas no burns occurred at locations for which the calculations indicated insufficient exposure. Figure 13 shows the calculated retinal irradiance, image diameter, and retinal radiant exposure as a function of time for a primate exposed to a high yield "low-altitude" detonation. The primate blinked seven times (cross-hatched areas) but failed to keep his eyes closed. The calculated integrated exposure during times when the eye was open was sufficient to produce burns in four of the exposures, and was borderline in two others. Actually the primate sustained five burns.

Lappin (110) used semi-empirical formulas for fireball growth provided by E. G. &G. (see Chapter IV) to compute retinal irradiance up to 150 ms. A figure of one-half of one percent of the total emission was assumed to occur during the first pulse, a figure which because of the small fireball size, makes the first pulse from weapons in the 5-40 KT size a distinct hazard. The equations for retinal irradiance used by Lappin appear below.

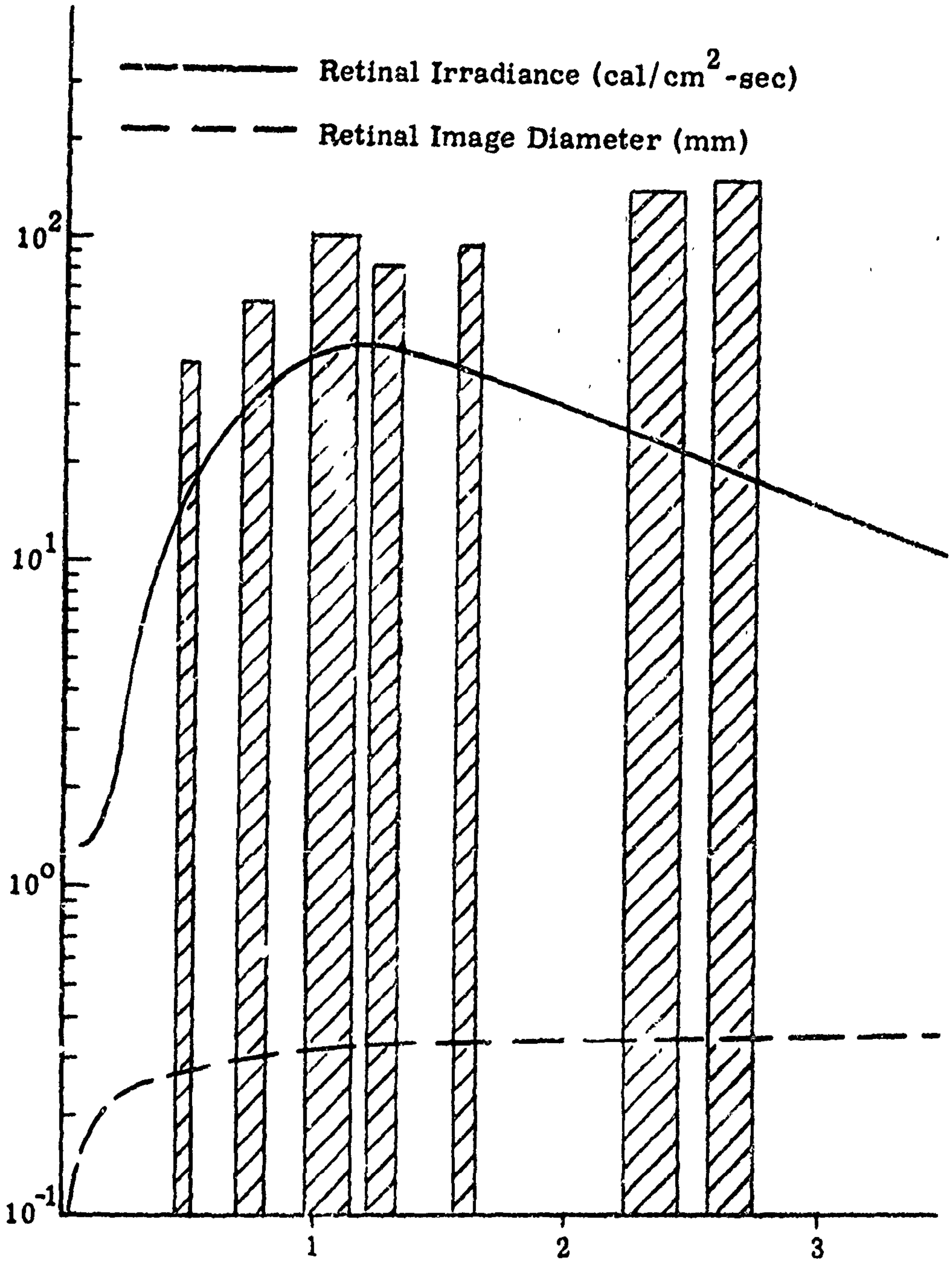

Figure 13 - Retinal irradiance as a function of time for primate exposed to high yield, low altitude detonation. Cross-hatched areas indicate periods when monkey's eyes were closed, open areas indicate periods when retinal exposure occurred (43a).

a. 0.5 - 3 KT range

$$Q_{R1} = 0.202\ W^{0.264}\ D_p^{\ 2}\ T_1$$

$$Q_{R2} = 0.413\ W^{0.65}\ D_p^{\ 2}\ T_2$$

where Q_{R1} and Q_{R2} are the retinal irradiances (cal/cm^2) from the first and second pulses, respectively, in the first 150 ms, W is the yield in KT, D_p is the pupillary diameter in mm, and T_1, and T_2 are the product of all transmission factors in the first and second pulses, respectively.

b. 5 - 40 KT range

$$Q_{R1} = 0.202\ W^{0.264}\ D_p^{\ 2}\ T_1$$

$$Q_{R2} = 9.17 \times 10^3\ \frac{W\ D_p^{\ 2}\ T_1}{D_f^{\ 2}}$$

where D_f is the fireball diameter determined from the equation:

$$D_f = \left[3.6 \times 10^{-3}\ W^3 - 2.1 \times 10^{-1}\ W^2 + 5.0\ W + 68.7\right] t^{0.2}$$

The solution to the 5-40 KT range equations for a 4 mm pupil, neglecting atmospheric transmission, appears graphically in Figure 14. It is apparent from this graph that if atmospheric attenuation is small, retinal burns can be produced by the first pulse of intermediate size weapons. In fact, Fixott, Pickering, Williams, et al. (58), did report that 4 of 13 rabbits behind early-closing shutters located seven and a half miles from an intermediate yield detonation received burns from the first pulse. All of the lesions from the first pulse were described as "mild and small".

Mirarchi and Hatheway (135) developed a retinal burn prediction method and have described a series of sample problems to which the technique has been applied. The essential features of their method are: (a) actual test information is used to provide yield-time data for a variety of weapon sizes, (b) ENW scaling laws are used to extrapolate these data to other

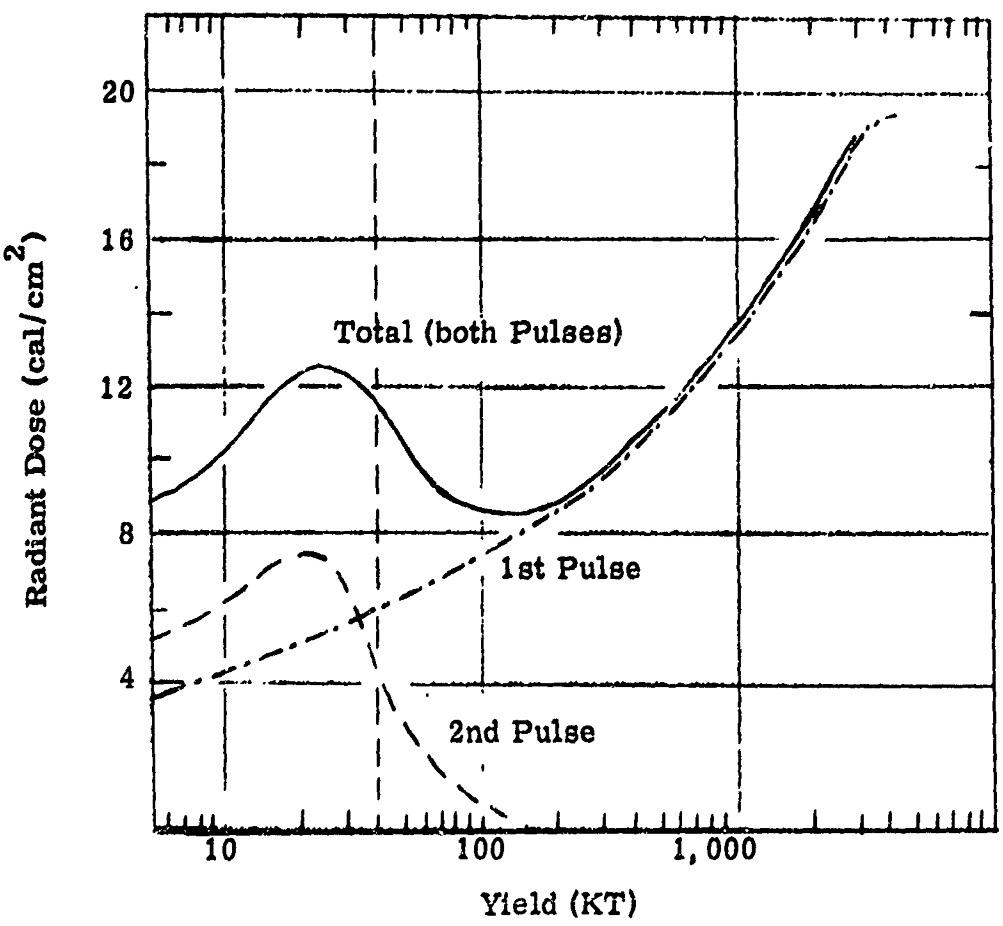

Figure 14 - Total retinal irradiation from the first 150 milliseconds after detonation assuming a 4 mm pupil and no atmospheric attenuation (from reference 110). Data to the left of the broken vertical line were computed using semi-empirical formulas for fireball growth. Extrapolation of curves to the right of the vertical line were made without benefit of fireball growth data.

yields, (c) atmospheric transmittance equations are modifications of those developed by Stewart and Curcio (see Chapter IV), (d) unpublished data provided by the 6570th Aerospace Medical Research Laboratories were used to specify transmission of the human eye, (e) reflection from the eye is used to further reduce the direct radiation in the eye, and (f) the resultant retinal irradiance is compared to data reported by Ham, et al. (86), for production of minimal lesions in the rabbit retina.

H. Summary

Threshold doses for chorioretinal burns have been shown to depend upon retinal pigmentation, retinal image size, retinal irradiance, and pulse duration. Models of the thermal characteristics of the eye are available for predicting time-temperature profiles. The relationships between such profiles and burn thresholds require further definition.

Although accidental or intentional cases of human exposure to nuclear detonations or laboratory photocoagulators have been too infrequent or included too small a range of values to validate thresholds derived from animal studies, the results do tend to confirm predictions based on the animal work. Reports of visual scotomas without visible lesions in the human retina do suggest, however, that exposures less than the thresholds for minimal observable lesions in animals may exceed the threshold for impaired visual function in humans. In the range of dose levels from below observable lesion threshold to suprathreshold, there may be a continuum of damage mechanisms from selected enzyme inactivation (producing no visible lesion), protein coagulation, to actual physical disruption of tissues. The histopathology, clinical manifestations, and ultimate ophthalmalogic effects will vary accordingly. From the experimental standpoint, the greatest research difficulties are: (a) assessing damage/no damage, (b) determining the mechanisms of damage, and (c) for the intact experimental animal, assessing the degree of functional impairment.

The location of the burn will determine the significance of the burn to vision. Unless a burn in peripheral retinal areas produces hemorrhage or destroys particular nerve bundles, the victim may be completely unaware of the lesion.

Although there is no generally recommended treatment for retinal burns, corticosteroid therapy may speed the reduction time of the lesion and may even result in decreasing its area. Results of research on mechanisms of damage may suggest important avenues of research on therapy.

Burns of the iris and cornea do not appear to be of significance compared to other injuries produced by exposure to nuclear detonations.

V. FLASH BLINDNESS

A. Introduction

The retinal effects of high intensity light range from the production of negligible temporary visual impairment to the production of permanent blinding scotomas. Both the temporary decreases in visual performance as well as the permanent effects may represent serious threats to safety or to mission success in a variety of situations. A recent report of an Air Force research project (169) included the statement, "this problem of chorioretinal burns is currently under investigation; however, in terms of the successful completion of an assigned operation, it will not be as serious a problem as flash blindness." Flash blindness has been defined as the temporary loss of vision resulting from photostress, and photostress as that condition resulting from exposure to a high-intensity light source from which an afterimage develops.(169). Because of the recent increase in interest concerning flash blindness, a number of studies have been initiated to obtain data useful in understanding the phenomenon of flash blindness, and means of reducing its effects.

B. Dark Adaptation

The phenomena associated with dark adaptation are well known, and numerous studies have been published which described adaptation to low light levels (9, 40, 41, 89, 90, 117). Classical explanations of dark adaptation relate increased sensitivity to the regeneration of photo-sensitive pigments following the degeneration of these pigments when exposed to bright light. Actual measurements of pigment concentrations have tended to support these explanations, although the relationship between sensitivity and pigment concentration is reported to be logarithmic rather than linear (185a). Classical dark adaptation studies generally employed bleaching light intensities much lower than may be produced by nuclear weapons. However, observations of the effects of lower intensity flashes may help us gain an understanding of the higher intensity phenomena.

Thresholds for visibility of test objects following adapting flashes of light are usually expressed as the required test object brightness. However, Crawford (41) transformed the recovery curve of thresholds against time into one of "equivalent background" against time. To do this, Crawford measured the required brightness of a steady background for threshold visibility of a test object, plotted a threshold versus background brightness curve, and then merely substituted the equivalent background values for thresholds. This procedure has intuitive appeal in that dark adaptation may be regarded as a decrease in "noise" or veiling light. Small afterimages produced by exposure to well-defined sources are then merely localized "noise" in the visual mechanism. Curves of threshold versus background brightness have been measured for a variety of test stimuli, and the resultant curves relating equivalent background with time after a flash found to be independent of the test stimulus parameters. For example, predictions based on data obtained with a test object subtending a 0.5^{o} visual arc were found to correspond closely to measured recovery from flashes when observing landscape scenes, a zeppelin against the clouds over Hamburg harbor, and other scenes.

Recently Barlow and Sparrock (9) demonstrated that the reduction in intrinsic noise, or afterimage, is due not only to the regeneration of the visual pigments but also to an "automatic brightness control" which reduces the sensitivity of the bleached retinal area. This latter feature explains why there is no lasting subjective impression of veiling light after bleaching by exposure to a large bright light. In the case of small afterimages, Barlow and Sparrock were able to match the equivalent brightness to stabilized test images and measure the "fade" caused by this automatic brightness control. The authors concluded that "bleached pigment in the receptors does not make them unresponsive to light, it makes them noisy"; the visual system then readjusts the brightness sensitivity in the bleached area, which increases visual thresholds.

It appears that one of the most productive means of describing flash blindness will be to employ Crawford's "equivalent background" concept. Reduction in equivalent background over time can then be related to the combined effects of regeneration of visual pigments and the automatic changes in retinal sensitivity described by Barlow and Sparrock. Experimental studies of flash blindness have employed a variety of test stimuli and criteria, with results which are often different and which may even appear to be contradictory. Use of the equivalent background concept might eliminate most differences due to these and to procedural variables.

Many investigators have reported wide individual differences in rate and final level of dark adaptation. McFarland and Fisher (117), and later McFarland, Domey, Warren, and Ward (118) examined large numbers of subjects covering a wide age range (teen-age to 89 years). Terminal dark adaptation thresholds were found to be correlated with age to a phenomenal degree (correlation coefficient of 0.84 between age and final threshold). Domey, McFarland, and Chadwick (53) derived a mathematical model of dark adaptation as a function of age and time and concluded that rate was a curvilinear function of age. Wolf (195) found a sudden increase in sensitivity to glare at the age of 40 and attributed it to entopic scatter of light by increased opacities of the lens. As a result of the above findings, rate of recovery from extremely bright light flashes should be investigated for a relationship to age of the observer. Unfortunately, few flash blindness investigators have reported the ages of their test subjects.

C. Laboratory Exposures to High Intensity Flashes

Recently several investigators have described the results of laboratory measurements of recovery of visual function after exposure to high intensity flashes. A series of experiments conducted at the School of Aerospace Medicine (166, 167, 169, 170, 171) compared recovery times as a function of flash intensity, pupil size, and test patch luminance. The flash source was a modified Zeiss light coagulator which produces a cone or diffuse light subtending 63^{o} 20' at the eye. Results appear in Table 4. The report of the first study (168) stated that "Variation between subjects was generally greater than that within subjects, indicating that they responded differently". However, an examination of the data indicates that variation between three of the subjects was small, particularly with the 0.014 mL*test light. The fourth subject differed markedly from the other three at nearly all test conditions. A later report (167) mentioned that an additional 16 subjects had been studied and that preliminary results demonstrated recovery times ranging from 10 to 50 seconds for recovery from a 2.3 x 10^{4} mL flash. The final results (171) described recovery times for only 15 subjects (aged 23 to 42 with 20/20 visual acuity), with a maximum range of less than four to one at any test condition. A summary of the results for the 15 subjects appears in Table 4. The authors concluded that a linear relationship describes recovery time as a function of intensity over the range studied. The slope of this relation was greater for the large pupil than for the small(pupil size more important as intensity increases). A later study (169) included an additional 40 subjects (visual acuity of 20/20 or better) all of whom were tested with pupil dilated. The visual test conditions were reported to correspond to those required to read aircraft instruments that are normally red-lighted. The results were not significantly different from those obtained in the preceding study (171) except for the finding that discrimination of a Landolt ring gap required slightly less time than did discrimination of a flashing test light.

Metcalf and Horn (127) used a smaller flash source (3^{o} 58' at the eye), higher illuminances, and an artificial pupil to control pupil size. Four subjects were exposed to flashes of varying intensity and then required to discriminate a brightness contrast corresponding to several lighting conditions

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*mL = millilambert

for aircraft instruments. The flash source was a high intensity carbon arc. A straight line relation between recovery time and logarithmic increase in illuminance was reported. The results were extrapolated to indicate that recovery times of about 170 seconds would be required when the burn threshold dose was approached. Some of the results are summarized in Table 4.

Brown (19) used a xenon arc equipped with an infrared filter to study recovery from high intensity flashes. The flash source subtended a visual angle of 15° at the eye. Two subjects were studied using three flash intensities, two recovery test criteria at each of five luminances, and with a variety of intervening filters. The results when no protective filters were used appear in Table 4. Brown also compared recovery times when the duration of the flash was reduced by one-half and the intensity doubled. Total energy appeared to be the dominant variable, although there was some indication that immediately following the flash the higher energy rate (shorter flash) reduced visual sensitivity more.

Verhuel, Lowry, and Brown (184), and Whiteside (192) have cited a report by Green (80) in which visual recovery times after exposure to a photoflash bulb were measured. The flash source subtended a 3.5° visual angle. "The subjects were almost completely blinded by the flash for a period of 15 to 20 seconds." In addition, a large white card was used as a reflector and the flash used to illuminate the card to about half the luminance of the bulb viewed directly. Although the image size was much greater, the recovery was much faster. This condition might be comparable to the reflection of a nuclear flash off a cloud in front of an observer facing away from the detonation.

Hill and Chisum (93) evaluated the effects of very short high intensity flashes (33 microseconds to 9.8 milliseconds). The flash source was a xenon-filled helical flash lamp with a diffusing globe which subtended a visual angle of about 10°. The illumination was not uniform across the entire globe. Complete data were obtained from one subject, and confirmed by less extensive measures with two additional subjects. Some of Hill and Chisum's results are summarized in Table 4. The authors report that, in general, the relations observed among recovery time, display luminance, display acuity requirements, and flash luminance are of the same form as those reported by Brown (19) for flash durations approximately 100-3,000 times longer. Principal conclusions from the study are:

(a) For a given flash luminance, the recovery time is a decreasing negatively accelerated function of display luminance. There appears to be little to be gained by providing display luminance greater than 100 mL.

(b) Recovery time decreases with decreasing luminance of the flash and decreasing visual acuity requirements of the display. However, reducing visual acuity requirements of the display has little effect when the display luminance is above about 3 mL and the sizes of the display symbols are already well above threshold values.

(c) Recovery time appears to be a positively accelerated function of total energy for flashes greater than about 10^3 mL-sec.

(d) A sixty-fold decrease in duration for two flashes of equal total energy required only twice the recovery time. There are some data to indicate that reduction in duration below 165 microseconds would not produce a proportionately shorter recovery time. Hill and Chisum did cite a paper by Brindley (15) in which evidence was presented to show that brightness is constant for constant intensity x time product with an integrated luminance of 0.3 mL-sec and flash durations as short as 3 microseconds.

Whiteside (191, 193) described experiments in which the solar disc was magnified to subtend about a 7.5° visual angle and was observed foveally for varying periods of time. Comparison of recovery times appears in

Figure 15. When the integrated stimulus intensity exceeded about 3×10^7 mL-sec, the recovery times increased rapidly. This dose was received during a 2 second exposure to the solar disc and produced an afterimage which persisted for a week to ten days. It is therefore probable that mild retinal damage was produced by this dose. Reciprocity for constant "brightness time product" was reported for up to 9×10^4 mL-sec. However, the shortest exposure times were much greater than those used by Hill and Chisum (93).

Fry and Miller (64a) describe the results of a recent study where luminance and exposure duration were varied to determine the effects upon flash recovery. Of interest here was the relationship between duration of high-luminance exposure and the operating requirements of eye protective devices. The question was: is the total energy received in a brief exposure the determining factor in recovery time (i.e., is there reciprocity between exposure duration and luminance). If so, then the higher the luminance anticipated, the faster the protective system must be activated. Conversely, if deviations from the reciprocity relationship are large for brief exposures, with a loss of "flash effectiveness", then the response time requirement for protective devices is less stringent. Flash exposures evaluated experimentally covered a range from 0.042 to 1.40 msec, and maximum field luminance was 4.4×10^8 mL. Test letter luminance for determining recovery time was 0.066 mL, and subtended visual angles from 41.9 to 10.25 minutes of arc as viewed by the subject. Mean recovery time after exposure to fields subtending 2.5^o or more ranged from 14.22 seconds (0.042 msec flash) to 109.71 seconds (1.401 msec flash). For a field subtending only 20 minutes the recovery times were much shorter and were not consistently related to flash duration. The results of this study together with the results of Metcalf and Horn (127), suggest that the reciprocity relationship between duration and luminance for recovery of visual function holds for flashes ranging from 42μ sec to 100 msec. Recovery is relatively independent of field size (2.5^o or greater). It is also interesting to note that infrared radiation in the flash has little to no effect on recovery times.

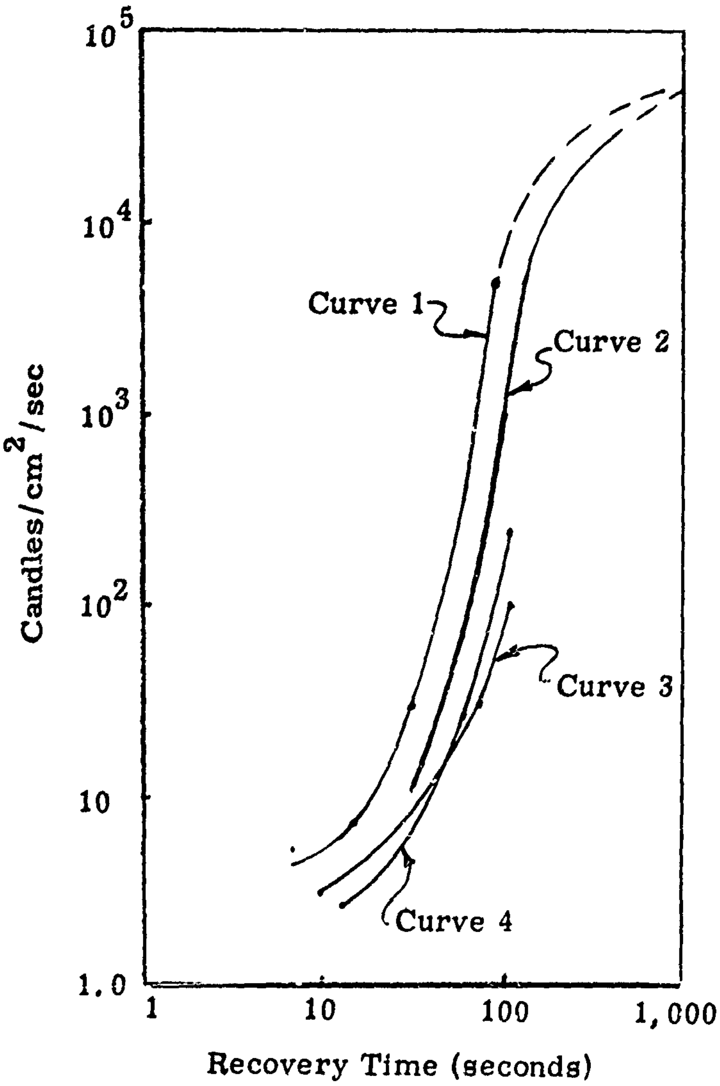

Figure 15 - Comparison of flash blindness recovery time in several experiments (from Whiteside, reference 192). Curve 1, recovery of daylight adapted eye to 0.14 ft/L after exposure to nuclear flash (upper point) or calibration source (lower points). Curve 2, recovery of dark adapted pupil to 0.03 ft/L after viewing solar disc. Curve 3, recovery to 0.07 ft/L after searchlight exposure (Metcalf and Horn, 127). Curve 4, recovery to 0.14 ft/L (Crawford, 41).

Parker (150) reviewed many of the studies described above. His conversion of the flash and recovery test conditions into a common set of units represents a significant convenience and many of these converted values are included in Table 4.

D. Flash Blindness from Nuclear Detonations

In addition to studies conducted in the laboratory or which used the solar disc as a light source, several measurements have been reported of recovery times after exposure to the light from nuclear detonations. Although details of the flash characteristics are somewhat vague (presumably due to security restrictions) in some reports, they still provide interesting empirical data. Whiteside (193) observed the first 102 ms of a nuclear fireball, then measured the time to detect three test fields of different brightness. The results appear in Table 5. The total dose at the corneal plane was computed from calibrated film records. Whiteside compared the recovery times for foveal location of the image to that for a location 3^{o} lateral to the fovea and found that the times were linearly related and nearly identical for discrimination of the test field through the afterimage (these results apply only to adaptation in the phototropic range).

Gulley, Metcalf, Wilson, and Hirsch (83) have reported a series of field studies in which flash recovery times were measured at the Nevada test site. Their report was directed at determining the threat of flash blindness to tactical air operations. Four to eight subjects were exposed to three nuclear detonations, some with and others without protective devices. In addition, rabbits were exposed to five nuclear detonations. Results of the exposures appear in Table 5 at the end of this section. The following relationship between peak illumination and peak thermal irradiance was derived (see Figure 7 in Section IV): peak lumens/ft^2 = 3.8×10^5 x peak thermal irradiance (cal/cm^2-sec).

The protective shutters closed in 500μs and had a 20% transmission when fully open. Experiments were run both with shutters operative and inoperative or with subjects behind a sandblasted window (diffusing screen). Visual recovery was measured with a nyctometer with a background luminance of 0.4 mL, or by the ability to correctly read four aircraft instruments illuminated with standard Grimes edge lighting, as well as standard red flood lighting. Recovery times for subjects behind the sandblasted window were similar to those reported by Severin, et al. (171) using 150 ms pulse flashes of similar peak intensity. It is likely that the blink reflex protected the subjects behind the sandblasted windows from more pronounced effects since the rise to peak intensity required 200 to 300 ms.

Verhüel, Lowry, and Browning (184) described an experiment in which three groups of subjects were oriented at 90, 135, and 180 degrees from the line of sight to a fractional KT (1.2 T) detonation. All 25 subjects were light adapted, unprotected by goggles and located slightly over a mile from the burst. Immediately after the shot, visual acuity was measured and visual targets identified. No dazzle or flash blindness were reported by any of the subjects. The authors concluded that during daylight, and at distances of a mile or more, there will be no significant dazzle effect from 1 to 5 T nuclear bursts when observers are looking more than 90^{o} from line of sight to the burst. No data were presented regarding the absence or presence of reflecting sources, such as clouds.

Verhuel, et al. (184) cited data from the Ophthalmological Survey Group which studied the Hiroshima and Nagasaki casualties, and no case of flash blindness lasting more than about 5 minutes was reported. The authors also reviewed flash blindness reports from a number of previous observation experiments. A group of light-adapted subjects located in an aircraft at 15,000 ft, 9 miles from a low air burst (10-20 KT) either looked directly at the flash or were oriented 180^{o} from the flash. Those who were facing away from the flash experienced no visual impairment, while those who viewed the flash directly had either no impairment or a temporary reduction in acuity ranging up to slightly less than 20/400, with complete recovery in less than 2 minutes. In another experiment, dark adapted individuals at ground level viewed a 10-20 KT flash from 10 miles. Unprotected subjects regained good mesopic vision in 132 seconds; ability to distinguish form at 0.001 mL required 310 seconds, and 671 seconds was required to distinguish form at 0.00001 mL. The absolute scotoma immediately after the burst was described as large and white or yellow-white. It was irregular in shape and covered 15-25° of the visual field. It decreased to 4-6° within 30 seconds and became progressively less "dense". A United Kingdom report of flash blindness was also cited by Verhuel, et al. (184). In that report an observer at an altitude of 48,000 ft and 10 miles from a detonation was completely blinded for 2 minutes and recovered useful vision in 5 minutes. However, the afterimage persisted for 12 hours. Since the observer's line of vision was about 25° from the line of sight to the detonation, the afterimage was peripherally located.

Comparison of the laboratory experimental results with those of observations of nuclear detonations is difficult. Spectral characteristics of the weapons vary from test to test and may deviate appreciably from those sources used in the laboratory. In addition, since appreciable thermal energy continues to be radiated after the minimum blink reflex time, for atmospheric bursts greater than about 5-10 KT, individual differences in blink response may influence the results. Those experiments in which shutters were employed provide results which are consistent with the laboratory findings. Whiteside's (193) data are in close agreement with the laboratory data, particularly if the nuclear exposure is considered of non-uniform intensity during the 100 ms exposure. Peak intensity would then be greater than 1.37×10^8 mL, a level at which there is some evidence of reduced efficiency of light in increasing recovery time (due to saturation of the visual pigments) during short exposures. High levels of illumination on the visual task have been shown to reduce recovery times to less than 10 seconds for peripherally located flashes below the burn threshold. Recovery of complete dark adaptation may require tens of minutes, but this is not a problem unique to the nuclear era since even conventional gun flashes may produce a decrease in visual sensitivity for several minutes in the dark adapted subject.

Table 4

Summary of Laboratory Studies of Flash Effects [(expanded from Parker (150)]

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec.)	Number of Subjects	Visual Task and Luminance
168	64	150	9.6	7-10	a) 3-4 b) 7-9	4	25 mm target flashing on and off at 1 second intervals, luminance of; a) 0.06 mL b) 0.014 mL Target subtended 40' visual angle, was located 12^{o} from fixation point (recovery times are ranges of means of five trials for each subject).
	5.4×10^{2}	150	81	7-10	a) 4-8 b) 9-18	4	
	10.8×10^{2}	150	1.6×10^{2}	7-10	a) 5-9 b) 16-26	4	
	2.7×10^{3}	150	4.0×10^{2}	7-10	a) 6-11 b) 19-37	4	
	5.62×10^{3}	150	8.4×10^{2}	7-10	a) 9-21 b) 31-52	4	
171	8.6×10^{3}	150	1.3×10^{3}	6-8.8 mean of 7.62	a) 6-18 mean 10 b) 9-33 mean 18	15 15	Same as 168 above.
				1-3.5 mean of 2.15	a) 6-12 mean 9 b) 11-28 mean 20	15 15	
	1.5×10^{4}	150	2.3×10^{3}	6-8.8	a) 10-32 mean 17 b) 16-47 mean 28	15 15	
				1-3.5	a) 8-17 mean 12 b) 15-44 mean 28	15 15	

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Table 4 (Cont'd.)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec.)	Number of Subjects	Visual Task and Luminance
171 (Cont'd.)	2.4×10^4	150	3.6×10^3	6-8.8	a) 14-44 mean 28	15	Same as 168
					b) 25-68 mean 44	15	
				1-3.5	a) 9-27 mean 17	15	
					b) 16-66 mean 37	15	
169	8.6×10^3	150	1.3×10^3	dilated	a) mean 16 c) mean 11	40 40	a) Same as 168 above, c) discrimination of Landolt C ring of 0.06 mL luminance.
	1.5×10^4	150	2.3×10^3	dilated	a) mean 26 c) mean 18	40	
	2.4×10^4	150	3.6×10^3	dilated	a) mean 38 c) mean 29	40 40	
127	5×10^6	100	5×10^5	6	a) 5 b) 12 c) 35 d) 93	4 4 4 4	Detect flashing of a circular patch (17 minutes of visual angle) with luminance of: a) 76 mL, b) 7.5 mL, c) 0.49 mL, and d) 0.08 mL.

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Table 4 (Cont'd.)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec.)	Number of Subjects	Visual Task and Luminance
19	1.34×10^4	900	1.2×10^4	5	0.13 vis. acuity	2	Resolution of a visual grating pattern (1^o size) to 0.13 to 0.33 visual acuity when illuminated to a) 0.2 mL, b) 0.56 mL, c) 5.6 mL, d) 1.8×10^2 mL, and e) 1.8×10^4 mL.
					a) 1	2	
					b) 1	2	
					c) 2	2	
					d) 3	2	
					e) 5	2	
					0.33 vis. acuity	2	
					a) 1	2	
					b) 1	2	
					c) 3	2	
					d) 4	2	
					e) 6	2	
	5.4×10^4	900	4.9×10^4	5	0.13 vis. acuity	2	
					a) 2		
					b) 2		
					c) 6		
					d) 9		
					e) 18		
					0.33 vis. acuity	2	
					a) 2	2	
					b) 2	2	
					c) 6	2	
					d) 12	2	
					e) 17	2	

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Table 4 (Cont'd.)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec.)	Number of Subjects	Visual Task and Luminance
19 (Cont'd.)	1.1×10^5	900	9.7×10^4	5	0.13 vis. acuity		
					a) 2	2	
					b) 3	2	
					c) 9	2	
					d) 19	2	
					e) 25	2	
					0.33 vis. acuity		
					a) 2	2	
					b) 3	2	
					c) 10	2	
					d) 13	2	
					e) 27	2	
80	1.7×10^4 (3.5° source)	30	5.2×10^2	--	15-20	--	
	9×10^3 (reflection from large plane)	30	2.7×10^2	--	2-3	--	Return of normal vision.
93	1.25×10^6	9.8	1.2×10^4	5	0.13 vis. ac.		Acuity grating with display luminance of: a) 0.01 mL, b) 0.03 mL, c) 1 mL, and d) 10 mL.
					b) 135	2	
					c) 15	2	
					d) 10	2	
					0.33 vis. ac.		Graph scales were such that recovery times are only approximate.
					b) 142	1	
					c) 15-20	3	
					d) 8-12	3	

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Table 4 (Cont'd.)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec.)	Number of Subjects	Visual Task and Luminance
93 (Cont'd.)	4×10^5	9.8	3.9×10^3	5	0.33 vis. ac.		
					b) 25	1	
					c) 7	1	
					d) 2	1	
	1.25×10^4	9.8	12	5	0.13 vis. ac.		
					a) 4	1	
					b) 2	2	
					0.33 vis. ac.		
					a) 19	1	
					b) 8-26	2	
					c) 2	3	
	4×10^8	0.165	6.6×10^4	5	0.13 vis. ac.		
					b) 110-150	2	
					c) 12-18	2	
					d) 8	2	
					0.33 vis. ac.		
					a) 140-150	2	
					b) 18-30	3	
					d) 8-15	3	
	4×10^7	0.165	6.6×10^3	5	0.13 vis. ac.		
					a) 32	1	
					b) 20	2	
					c) 5	2	
					d) 2	2	
					0.33 vis. ac.		
					a) 140	1	
					b) 22	1	
					c) 5	3	
					d) 2	3	
	4×10^6	0.165	6.6×10^2	5	0.33 vis. ac.		
					a) 58	1	
					b) 12	1	
					c) 2	3	

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Table 4 (Cont'd.)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec.)	Number of Subjects	Visual Task and Luminance
93 (Cont'd.)	2×10^{8}	33×10^{-3}	6.6×10^{3}	5	0.13 vis. ac.		
					a) 65	1	
					b) 12	2	
					c) 5	2	
					0.33 vis. ac.		
					b) 45-90	2	
					c) 5-10	2	
					d) 2	2	
	2×10^{7}	33×10^{-3}	6.6×10^{2}	5	0.13 vis. ac.		
					a) 5	1	
					0.33 vis. ac.		
					a) ~~25~~	1	
					b) 10-65	2	
					c) 2	2	
64a	4.4×10^{8}	0.042 to 1.4	1.85×10^{4} to 6.2×10^{5}	2 (artificial pupil)	Mean recovery time, 42 μsec flash, letter sizes 2.5° to 10° - 14.22 sec. With 1.4 msec flash, letter sizes 2.5° to 10°, mean recovery time 109.7 sec.	5	Test letter luminance 0.066 mL. Field size range 10.0° to 20' visual arc.

Table 5

Flash Effects of Actual Nuclear Detonations

Ref.	Yield (KT)	Peak Luminance (mL)	Flash Duration (ms)	Total Energy at Corneal Plane	Pupil Diameter (mm)	Recovery Criteria and Procedures
193	--	1.4×10^8	100	1.4×10^7 mL-sec.	4+	One subject viewed the fireball 3° off the fovea, then observed 1.1, 0.44, and 0.15 mL test fields. Foveal recovery times were 5, 17, and 58 seconds, respectively. Recovery times through the afterimage were 28, 40, and 89 seconds, respectively.
83	11.5	4.58×10^4 (estimated)	peak at 100 ms	0.05 cal/cm^2	--	Six animals exposed, four behind shutters and two unprotected. One of the unprotected animals received a minimal lesion. Location was 21,200 yards from ground zero in craft at undisclosed altitude.
	11.5	4.58×10^4	peak at 100 ms	0.0552 cal/cm^2	--	Six animals exposed, two behind inoperative shutter with 20% transmission, four unprotected. Three of the unprotected animals received minimal lesions. Location was on ground 17,600 yards from ground zero.
	10.3	1.29×10^5 (estimated)	peak at 100 ms	0.0833 cal/cm^2	--	Four humans and two animals located in a craft 19,360 yards from ground zero. All humans were protected by shutters (open transmission of 20%) which closed in 0.55 ms; no flash effects observed. Both animals were unprotected; one suffered a minimal lesion.

(continued on next page)

Table 5 (Cont'd.)

Ref.	Yield (KT)	Peak Luminance (mL)	Flash Duration (ms)	Total Energy at Corneal Plane	Pupil Diameter (mm)	Recovery Criteria and Procedures
83 (Cont'd.)	10.3	1.29×10^5	peak at 100 ms	0.1052 cal/cm^2	--	Four humans and three animals at ground level 15,136 yards from ground zero. Humans were protected by shutters (see previous page) and were unaffected by the flash. Animals were unprotected and two of the three received minimal lesions.
	74.1	6.8×10^4	peak at 300 ms	0.0963 cal/cm^2	--	Six humans and three animals exposed in an aircraft 32,426 yards from ground zero. Three of the humans were protected by inoperative shutters (20% transmission); recovery times to 0.1 and 0.3 visual acuity were 72 and 90 seconds for one subject; times to read aircraft instruments with standard edge lighting and red flood lighting were 10-12 seconds for the other two subjects. The fourth subject's shutter closed in 0.55 ms and recovery was virtually instantaneous. Two subjects were behind sandblasted aircraft windows and required 90 seconds to recover to 0.1 visual acuity. Two of the three animals (all unprotected) received lesions.

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Table 5 (Cont'd.)

Ref.	Yield (KT)	Peak Luminance (mL)	Flash Duration (ms)	Total Energy at Corneal Plane	Pupil Diameter (mm)	Recovery Criteria and Procedures
83 (Cont'd.)	18.7	14.2×10^4	peak at 250 ms	0.0347 cal/cm^2	--	Six humans and four animals exposed at ground level 18,304 yards from ground zero. Two of the humans were behind shutters which closed in 0.55 ms and one subject was behind a shutter which closed in 0.9 ms.. Recovery was instantanecus. Another subject was behind an inoperative shutter (20% transmission), behind a sandblasted diffuse window. Recovery took 6 seconds to read standard red-lighted aircraft instruments. The fifth subject was behind a sandblasted window, but without a protective shutter. Recovery to 0.1, 0.3, and 0.5 visual acuity required 20, 28, and 35 seconds, respectively. The sixth subject was behind a 20% narrow band filter and recovered immediately. None of the animals were protected and none received retinal lesions.

VI. EFFECTS OF COMMONLY USED DRUGS AND STIMULANTS ON THE PUPIL

During the course of an average day, major portions of the population are under the physiological influence of some drug or stimulant. Therefore, the question was posed: do any of the drugs or stimulants in common usage affect the vulnerability of the eye to light and thermal damage by influencing pupil size and pupillary dynamics. To determine if this was a significant problem, a review was made of the physiology/pharmacology literature dealing with the following classes of compounds:

a) miotics (cholinergic and anticholinesterase drugs usually used for the treatment of glaucoma).

b) mydriatics (parasympatholytic drugs used for ophthalmologic examinations)

c) tranquilizers

d) antihistamines

e) non-narcotic analgesics

f) barbiturates

g) non-barbiturate sedatives

h) psychic energizers

i) stimulants

j) coffee, tea

k) tobacco.

In general, the literature does not deal with quantitative pupillary effects, unless of course the drug is intended specifically for producing a pupillary reaction. Investigators may report that a compound has a "tendency toward mydriasis" (or miosis), but the net pupillary effect is determined by a host of physiological variables and interactions.

The miotic and mydriatic drugs do produce their respective effects which can persist for hours or days. However, these are administered to such a small percentage of the population at any one time that they are probably not of statistical significance.

Of the tranquilizers, reserpine seems to produce the greatest tendency toward mydriasis. However, this would require fairly heavy dosages and these patients are not likely to be in a situation where they would be exposed to the fireball image.

The antihistamines are parasympatholytic and augment the action of adrenalin, thereby producing a tendency toward mydriasis.

Amphetamine, though it possesses a mydriatic action when applied topically, was not reported to produce pupillary effects when administered systemically.

Although coffee, tea, and cocoa produce a variety of physiological effects, it is doubtful if they are able to offset the effects of ambient light, with regard to pupil size. Effects of tobacco in normal quantities would also produce only small tendency towards miosis, if any effect at all. Both nicotine and caffeine in large doses would produce pronounced effects, but an insignificant number of people receive such doses.

In summary, the majority of the drugs which were reviewed had little effect on pupil size in dosages customarily encountered; by far, the most important determinant of pupil size is the level of ambient light. Except for individual drug reactions or cases of heavy over-doses, the pupil size would be expected to be normal under day light conditions.

Inasmuch as the full pupillary reflex is slower than the blink reflex, changes in pupillary dynamics would have no real significance for pulse durations less than a second, but could be important for individuals exposed to multimegaton atmospheric detonations. Since pupillary reflexes are affected by both drugs and a number of diseases, certain elements of the civilian population who do not keep their eyes closed may receive different retinal doses, depending upon the speed of their pupillary reflex.

The intentional application of miotic drugs as a protective measure has been suggested for Air Force personnel (133). However, use of presently recommended fixed filter devices has many advantages over artificially induced miosis, particularly for large population groups.

VII. HUMAN BEHAVIOR: REFLEX BEHAVIOR WITH AN INTENSE LIGHT STIMULUS, AND RESPONSE TO SUDDEN VISUAL IMPAIRMENT

Most of the flash blindness and retinal burn literature deals with the eye and the photostress response as an isolated phenomenon. Little attention is given to the total organismic response to an intense light stimulus or to the behavioral sequelae to sudden visual impairment. Therefore, as a part of this review, a preliminary investigation was made of motor behavior patterns to an intense light stimulus, and of the possible individual reactions to sudden visual impairment. In neither case is there an abundance of experimental data. However, there is enough information to recommend these as significant areas deserving further research.

A. Behavioral Response to an Intense Light Source

For situations where a low yield, tactical weapon is detonated in the atmosphere or any weapon is detonated at very high altitudes, the fireball pulse is so rapid that no motor responses of the individual will have an effect upon protection of the eye. The image either is or is not within the line of vision. However, when high yield strategic weapons are detonated within the atmosphere, the fireball duration is long enough to permit several reflex motor actions.

When the fireball image appears directly on the fovea, there is little protective action that will occur until the blink reflex is complete. It is assumed that the blink will be completed in about 100 to 150 milliseconds. With a large, intense image, there is almost absolute certainty that the blink reflex will take place. When the image is small, as would be the case with a distant atmospheric detonation, and novel, as any detonation would be, there is <u>less</u> certainty that the blink will occur within 150 milliseconds or that the individual will keep his eyes closed after the first blink. The novelty of the stimulus combined with the curiosity drive of primates could conspire to make such behavioral predictions less certain.

The second, and more likely situation is one where the fireball image would fall in some extrafoveal region. In this case, it is even less certain how soon blink would occur, and in fact, there may be other reflexes as well.

There has been research done with animals and humans to describe the optokinetic response, orienting reflexes, and curiosity (4, 14, 27, 156, 175). In general, this can be summarized as follows: a novel stimulus, visual or auditory, presented outside the field of immediate attention has a strong attracting influence if it is sufficiently above the level of ambient stimuli. In fact, it is difficult for human subjects to voluntarily suppress the optokinetic and orienting reflexes.

It is well known that primates used during nuclear weapon tests have received multiple burns on the retina because they repeatedly opened and closed their eyes during exposure to the fireball (2). While it is difficult to ascribe this to curiosity or to some form of orienting behavior, it has occurred repeatedly, and without explanation.

Very little is known about these behavioral patterns in humans, and until they can be experimentally determined, casualty prediction estimates will be incomplete.

B. Behavioral Response to Sudden Visual Impairment

Adverse behavioral responses may be one of the problems faced by combat troops or civilians who suddenly experience flash blindness. What unusual behavioral problems might arise, how could these persons be helped, what is the value of education and training, etc. are questions which need to be answered.

The first and most obvious source of information was the case reports of individuals who had accidentally sustained retinal burns during nuclear weapon tests (3,42,,159). In almost all cases, the victim was able to attend to his assigned task even though aware of a persistent afterimage. The afterimage did interfere with the driving ability of one of the individuals, but enough vision was retained in the non-damaged areas of the retina to permit normal personal activities (42).

However, it should be pointed out that the psychological climate of the test environment is considerably different from that associated with weapons detonated in acts of war. More specifically, these individuals were aware of the fact that viewing the fireball with the unprotected eye could result in eye damage. Secondly, they expected the detonation to occur and they knew they were not at war.

To pursue the question from the standpoint of behavioral reactions to visual loss during a disaster-associated condition, questions were asked of ophthalmologists, rehabilitation personnel, social workers, psychiatric counselors, and administrators of blind institutes. In addition, literature was reviewed for anecdotal accounts of battle field casualties (194). The information is very scarce: persons who first encounter the traumatically blinded are seldom disposed to make detailed behavioral observations. Traumatically blinded persons are often in a poor position to describe their immediate reactions because of shock, suppression of the traumatic incident, etc. (12, 29, 186).

Opinions by professionals who have worked with the blinded are varied: some predict that the individuals would be shocked, catatonic, and immobile. Others predict that panic would prevail. There was some consensus that that the response would depend on the degree of impairment and that the victims would readily respond to calm, directive instructions.

Undoubtedly, the individual reaction would depend upon: a) the person's psychological make-up, b) the nature of the situation, and c) the degree of familiarity the victim had with the threat from education or training.

The actual degree to which vision is lost would depend upon the exposure conditions. In most cases, some vision would probably be retained in a portion of the retina. Second, the size of the afterimage would probably shrink very rapidly such that the person could look "around" the scotoma , after a few minutes. However, the aircraft pilot or ground vehicle operator might suffer other injuries as a result of the transient impairment. In all cases, training and education would be of great value.

VIII. COUNTERMEASURES

A. Introduction

The necessity for eye protection against light and thermal emissions of nuclear weapons was recognized early in the atomic weapons development program. Beginning with the first tests, observers have been provided with high density, fixed filter goggles. In fact, surprisingly few permanent eye injuries have been sustained by personnel directly viewing weapon tests. There have undoubtedly been many cases of flash blindness which have never been documented; these being largely the results of curiosity and disregard for warning. However, nuclear weapon test viewers have had the advantage of extensive precautionary measures and warning as to the time and location of the detonation.

As nuclear weaponry developed and more military deployment methods were made possible, it was readily apparent that the fixed filter goggle was not compatible with the variety of visual tasks performed by military personnel. Because the high density, fixed filter lens imposes such a restriction on day-time vision and is nearly impossible to use at night, this provided the impetus to investigate the possibility of developing dynamic filters. A filter was needed which in the inactive state provides fairly unrestricted vision, but when activated provides an optical density sufficient to protect the eye against the intense energy pulse. The technical precedent for a rapid-acting filter was probably the high speed shutter used in special purpose photography.

As early as 1951 in the Operation Buster series the Air Force was attempting to evaluate the seriousness of visual handicap (flash blindness) and the effectiveness of several protective devices. It was concluded at this time that the light/thermal effects did not pose a severe hazard to personnel at ranges where other effects were minimal. However, in the Upshot-Knothole series in 1953, investigators were concerned about the possible additional hazard associated with night-time dilated pupil. As a result of testing, the earlier conclusions were revised and it was shown that a 20 KT weapon could produce burns at distances up to 40 miles. In Operation Hardtack, 1958, with the high altitude bursts, burns were produced in experimental animals at distances out to 345 miles, representing line-of-sight limits for a weapon detonated at an altitude of about 50 miles (78). As a result of Redwing (1956) and Hardtack (1958), enough data were produced to emphasize the fact that the threat to the visual system encompassed thousands of square miles beyond the area where prompt radiation and blast effects would be present (10).

There has been considerable support for research and development programs on eye protective systems. The Army, Navy, Air Force, and Defense Atomic Support Agency (DASA) have all provided support to different technical approaches. DASA has had the task of monitoring and coordinating the over-all program of flash blindness, chorioretinal burn, and countermeasure research.

B. General Types of Devices

The operational approaches to eye protective devices can be divided into the following general categories:

1. Fixed Filter Goggles

As the name implies, the fixed-filter goggle uses a filter of fixed density to absorb or reflect radiant energy before it enters the eye. There are several physical methods for achieving this effect, but for all the opacity of the filter does not change as a function of ambient energy. The transmission characteristics of the fixed filter can be selected so that the transmission of visible light, infrared, and ultraviolet energies is attenuated.

In order to protect the eye against serious damage from the fireball, the opacity of the fixed filter must be so great that day-time vision is significantly hampered, and night-time vision is restricted to objects which are floodlighted. The fixed filter system must be worn permanently if it is to offer continuous protection and therefore it represents a compromise between the degree of opacity required for protection and the transmission necessary for vision when ambient lighting is reduced. However, despite this drawback, the fixed filter approach is reliable, inexpensive, poses no unusual logistic problems, and gives a predictable degree of protection.

2. The Monocular Eye Patch

The monocular eye patch system is a model in simplicity and reliability, but suffers some obvious drawbacks. First, stereoscopic vision is lost, plus restriction of the visual field. Second, the system has an effective operating cycle of one; if the exposed eye is injured, the covered eye becomes the sole visual resource of the victim.

3. Eye Slit Devices

A "peep-hole" or eye slit device is a possible consideration, much like the sunglasses devised by Eskimos. In the literature reviewed for this report, two references were found for such an approach. The first was a feasibility study of a louver system originally intended to protect the eye against shrapnel (182). The second was a plastic laminate louver, similar to the first, for providing both dazzle and ballistic protection (180).

The rationale for the peep-hole or eye slit shield is based on probability. Because the angle of vision is reduced while viewing through slits, it follows that there is a lesser chance that the fireball image will appear on the retina. The obvious limitation to this technique is restriction of visual field. However, in some military operations it is not necessary that the operator have an unlimited field of vision, so the eye slit shield may find acceptance as an effective compromise device.

4. Curtains and Screens

A variation of the eye slit technique is the use of a visor, screen, or lateral blinders, to restrict the field of vision. Again, the assumption is that if the fireball occurs at a point in space outside of the momentary field of view and if the individual does not involuntarily or voluntarily orient toward the source, he will be protected. On long range aircraft missions where navigation is done exclusively by instruments, there is little need for outside vision, and the crew could easily be protected by a curtain or screen which limits vision to a small segment of the canopy.

5. Dynamic Devices

The most desirable all-around system would be one that changed its optical density as a function of ambient intensity; when ambient lighting is normal, the lens is essentially clear, but when an intense source appears, the lens darkens. Methods for achieving this effect include:

a. placing a mechanical shutter in front of the eyes,
b. placing an opaque liquid, smoke, or aerosol material before the eyes,
c. changing the optical properties of the material by electro-optical or magneto-optical means to cause birefringence,
d. changing the optical transmission properties of the optical material by phototropic, photochromic, or thermotropic reactions,
e. using indirect viewing systems which present the viewer with an electronic image rather than a direct view of the source,
f. using tiny reflective dipole shutters which can be oriented in an electrical field.

All such dynamic systems would have to be "sensitive" to changes in ambient light (or other electromagnetic phenomena associated with the nuclear pulse). This dynamic quality of the filter system can be achieved through the filter itself which would be emr-reactive, or indirectly through an emr-sensing device which triggers the release of energy to produce a reaction within the filter.

C. Representative Devices and Operating Principles

1. Fixed Density Filters--Goggles, Visors, Full Face Shields, Canopy, Etc.

There are various means for creating a fixed density filter, causing portions of the incident energy to be absorbed or reflected. The majority of fixed density filters approach neutral density. That is, all wavelengths in the visible spectrum are absorbed approximately equally. The terms used to describe transmission or density usually apply to the visible spectrum, but it is also important to know transmission properties for ultraviolet and infrared. For example, some neutral density plastic optical materials will transmit significant amounts of ultraviolet and infrared (34). It would be more desirable to completely filter out those wavelengths which do not contribute to vision. Other properties of the lens should include good optical quality, abrasion resistance, low cost, flame resistance, thermal stability, a nonshatter tendency, etc.

Representative of neutral density filters designed specifically to protect against flash blindness are the gold visor (Air Force and Navy) and the Navy LRFG (Light Restrictive Flash Goggle).

a. 1% Gold-Covered Visor*

Developed by the Air Force, this filter is fabricated from neutral density plastic and is coated with gold. The coating material serves to reflect the majority of the incident energy, transmitting only 1% of the energy in the visible region. (As reference, good quality civilian sunglasses transmit only about 15% in the visible.) The gold filter has a peak transmission of about 2.5% in the 535 mμ region, and trails off to zero transmission at 375 mμ and 1,750 mμ, respectively. This visor is intended for daylight use only.

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*The gold visor has been recently changed to a 2% transmission value, rather than 1%, and adapted for daylight operations by the Air Force.

A mathematical evaluation of the retinal burn protection effectiveness of the 1% neutral density gold-coated filter was prepared by Lappin (110) at the Biophysics Laboratory, Wright-Patterson Air Force Base. The evaluation was based on conditions and assumptions regarding atmospheric transmission, blink reflex time, pulse characteristics of various yield weapons, and experimental burn threshold data.

Lappins' calculations indicate that the total retinal irradiance through the canopy and 1% filter for a 150 msec (millisecond) exposure to the first phases of fireball yields ranging from nominal (below 5 KT) to 3 MT will not exceed 0.10 cal/cm^2.

Inasmuch as the 1% filter has been changed to 2%, this retinal irradiance would be increased to 0.2 cal/cm^2/150 msec.

It should be emphasized that the pulse characteristics in the report are based on low altitude detonations where fireball growth is very slow compared with the growth rate for high altitude or upper atmospheric detonations. In these latter cases, the dose delivery rate would be significantly higher and the biological burn threshold lower. For a detailed relationship between irradiance level, image size, and exposure time, refer to the section in this report on chorioretinal burns.

Lappin (110) states at the end of the report that a similar analysis must be performed for assessment of the filter's ability to provide flash blindness protection.

b. Light Restrictive Filter Goggle

The 1% LRFG was developed by the Navy to permit the pilot to fly by visual contact during the day and to see floodlighted instruments at night. The LRFG goggle uses a red glass filter with a reflective metallic coating. In contrast to the transmission properties of the gold visor, the LRFG is a narrow band pass filter, transmitting about 10% in a peak around 725 mμ, with fairly sharp cutoffs at 550 and 900 mμ respectively. This goggle system has a restricted field of view (2) and it was reported at the 1964

NRC Committee on Vision Meeting that this system was being discontinued.

c. Other Fixed Density Filters

A good quality, general purpose sunglass will transmit about 15% of the energy in the visible spectrum and will have good cutoff of transmission in the ultraviolet and near infrared range (34).

Colored filters (green, amber, yellow, blue) are commonly used in sunglasses. The color of the lens shows that portion of the spectrum which passes through the lens to a greater extent than the other colors. That is, a green lens which has an average light transmission of 15% might pass more than 50% of the green. The rationale behind using the colored filter is that the colored "energy window" is selected to coincide with, and admit some color peculiar to the target, or to take advantage of peak photopic or scotopic sensitivity of the eye. The balance of the filtering action presumably absorbs portions of the spectrum which could reduce acuity. However, controlled experiments on target detection have not shown colored lenses to have any advantages over neutral density filters under conditions of fog or haze. In addition, colored filters also tend to distort color perception (59).

Reflecting lenses reduce light transmission by reflecting the incident light rather than absorbing it. This is achieved by partially silvering the glass or plastic surface with various metals or combinations of metals to get a half-mirrored surface. In the visible spectrum, these filters can be essentially neutral density (such as the Air Force gold visor), or they can be made to pass a particular bandwidth (such as the LRFG). However, reflecting lenses may pass a considerable amount of infrared, so the underlying material should be selected for its ability to absorb IR (59).

Polarized filters are also used to produce an optical density. A polaroid filter will selectively pass only those light waves vibrating in one direction, thus effectively reducing the total amount of light passing through the lens. Commercial polarizing lenses typically have a transmittance value of about

30%. They are intended to reduce reflective glare (which usually has a high component of uni-directional vibration). As fixed filters, they are not as effective as a neutral density lens (59), but the principle of polarization has been used in dynamic devices (discussed later).

For military use, it is a relatively straightforward process to evaluate the effectiveness and disadvantages of the fixed filter protective system. Although there is an obvious compromise between high optical density required for protection and lower optical density necessary for vision, the fixed filter is a currently used interim device for general flight operational conditions. *

For civilian use, the fixed density filter (sunglasses or ski goggles) is the only currently available protective device other than the eye patch. There are commercially available sunglasses which utilize a directly-activated dynamic material. These materials are phototropic (described later), and adjust their density to ambient levels. However, the reaction time to achieve a high density is too slow to provide protection against the rapid fireball development. Commercial sunglasses can be selected for particular desirable characteristics. For example, a good quality lens will have a transmission value of about 10%-20% in the visible region, less than 5% transmission in the ultraviolet range, and less than 20% in the infra-red (34). There is a wide range of quality in these glasses, so the civilian consumer should have a set of specifications against which to check the characteristics of any particular lens.

2. The Monocular Eye Patch

The eye patch system has been considered by British and U.S. military services and apparently is available to pilots, either as a back-up to the visor, or for use alone (55).

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*NRC Committee on Vision, Annual Meeting, April 1964, Washington, D.C.

3. Dynamic Devices

a. Mechanical Devices

(1) The Electromechanical Shutter

The electrically or explosively actuated shutter principle is a logical approach to a high speed closing device; this being an evolutionary step from high speed camera shutters. A generalized system of this type would employ a photo or thermal sensor to register the incident energy flux from the weapon pulse and the output signal would then be used to trigger the shutter system. Depending upon the design and operating principle, return to the open state can be automatic or manual. Using an opaque mechanical shutter, it is possible to attain a very high degree of optical density. However, in order to achieve high reaction speed, the shutter mass must be accelerated very rapidly. Therefore, it is desirable that the shutter be light in weight and that it move only a short distance. This goal can be accomplished by using two plates, each cut out with slots like a picket fence. When the plates are superimposed, light will enter through the space "between the pickets". When the device is activated, one plate advances and the pickets or grid lines cover the spaces in the other plate, thus occluding the passage of light.

The history of development of the electromechanical goggle goes back to 1957 when Wayne-George, Inc., began development work. In 1959, they published a report of their goggle system (185a), and various electromechanical shutter systems based on this design have been tested in Operation Plumbbob (1960), nuclear tests in 1962 (2), and in 1963 by an operational Air Force Squadron (61).

This system utilizes silicon solar cells as flash detectors, the solar cell output going to a separate electronics package. The signal from the electronic pack fires an explosive dimple motor which in turn drives one of the plates. After being activated, the user manually re-opens the lens and the system can be operated four times without replacing the dimple motors. These goggles have an open light transmission of 30% and a closed transmission of 0.01% (optical density of 4). The shutters were designed for closure in 250 μsec after the onset of flash, but field tests in 1960 (83) give a closure time of 550 $\pm$ 50 μsec.

In April of 1963, National Cash Register produced models of this electromechanical goggle for testing by an operational Air Force Squadron (61). The goggles were worn in the day and nighttime by pilots and aircrew in all phases of an ADC mission. The evaluation criteria were primarily comfort, visibility, and operating ease, rather than eye protection or activation time. The results were negative on the basis that:

1. the goggles imposed severe restrictions in vision for instrument and radar reading,
2. fliers reported vertigo, nausea, eye strain, and headaches as a result of wearing the goggles,
3. the system was incompatible with present design full pressure suits,
4. the subjects had difficulty re-opening the lens after activation,
5. there were light leaks,
6. the metal bars became scratched after several operations, and
7. there were accidental firings resulting from the light emitted by the standard strobe light landing approach system.

Some of these difficulties encountered could have been peculiarities of prototype goggles and the evaluation was not based on protective ability. However, the visual restrictions of the system were reported to seriously compromise flight safety in all mission phases, especially near the ground. Therefore, this goggle system was not recommended for use in ADC intercept missions.

b. Electro-Optical/Magneto-Optical Devices

There is a class of optical effects under the category of electro- and magneto-optics which can be utilized to attenuate light as it passes through special materials. Included under this general class of optical effects are the following phenomena: Pockel's effect, Maxwell effect, Cotton-Mouton effect, the Kerr effect, Faraday effect, and the Piezoelectric effect.

- Kerr effect--when a liquid (as nitrobenzene) is subjected to a strong electrical field, it becomes double refractory (birefringence--explained later).
- Piezoelectric effect is a general property of some unsymmetrical crystals, the surfaces of which acquire opposite electrical charges when the crystal is subjected to physical stress.
- Pockel's effect utilizes the piezoelectric property of transparent crystals to induce birefringence. When a clear piezoelectric crystalline medium is subjected to a strong electrical field, birefringence is induced.
- Faraday effect--when some materials such as quartz or flint glass are exposed to a strong magnetic field, they cause rotation of a beam of plane-polarized light when it passes through the crystal. This differs from rotation produced by crystalline media in that the direction of rotation is independent of the sense in which the field is traversed. The angle of rotation is proportional to the magnetic field strength and the path length of the material.
- Maxwell effect--when viscous liquids comprised of anisotropic molecules are flowing such that there is a shearing velocity gradient, birefringence is induced. The difference in refractive indices is proportional to the shear velocity gradient.
- The Cotton-Mouton effect is similar to the Faraday effect, producing double refraction for light propagated in directions at right angles to the magnetic field.

(1) The Kerr Cell

Electro-Optical Systems, Inc. (EOS) utilized the Kerr cell in preference to the Faraday cell or image converter tube because of the higher optical resolution available with the Kerr cell. This particular system was developed to show its feasibility for visual protection on optical viewing and optical fire control instruments. In these applications the requirement for high optical density is pronounced because of the light concentrating effect of the optical aiming system (88).

The Kerr cell, illustrating the phenomenon of birefringence, operates as follows: a thin-walled glass cell contains a solution of nitrobenzene and two electrodes. When a potential is applied to the solution, the polar nitrobenzene molecule orients itself in the electrical field and behaves as a uniaxial crystal. Light passing through the nitrobenzene molecule is double refracted. With the emergent light now refracted into two polarized beams vibrating at right angles to each other, it is possible to add polaroid filters at different angles to absorb the polarized beams. When the polaroids are crossed, the system will transmit light only when a voltage is applied. When the filters are parallel to each other, the incident light is attenuated only when the voltage is applied. It is in the latter mode of operation that the Kerr cell can be used as an eye protective system.

The operating characteristics of the Kerr cell are such that the time closure can be achieved in one to two microseconds. This includes the time delay for triggering the flash detector and applying a voltage pulse to the cell (40,000 volts). Opening or clearing time is practically instantaneous once the voltage is lifted.

The characteristics of the Kerr effect are a function of the purity of the nitrobenzene and the duration of the applied voltage. In practice, the Kerr effect can only be produced for a brief period of time before the magnitude of the effect is reduced. For example, optical density achieves its maximum in about two microseconds, but begins to decrease almost immediately. By 100 μsec, optical density has decreased to three, and by one millisecond, optical density is around one. This is the reason for incorporating a mechanical shutter as back-up. The mechanical shutter can be completely closed in a millisecond or less, so the Kerr cell is only required to maintain a high density until the shutter closes.

Another property of the Kerr cell is that the spectral absorption characteristics vary with the applied voltage. That is, at any fixed voltage the absorption is maximum for one wavelength and is less for wavelengths on either side. Therefore, in order to achieve uniform attenuation throughout the visible spectrum, a half-wave plate is added between the Kerr cell and the polaroids. The net effect is effective attenuation from below 400 mμ and above 700 mμ, giving an optical density of about 6 (0.0001% transmission). Unfortunately, the open transmission of the system is only about 10%. This 10% transmission does not include the additional restriction in vision imposed by the grid type shutter.

There are other considerations in addition to the low open transmission which impose restrictions on this type of system. First, the Kerr effect, being a molecular phenomenon, is temperature sensitive. Consequently, to maintain predictable spectral absorption characteristics, the nitrobenzene temperature must be regulated, or the applied voltage must follow temperature. This also places a restriction on Kerr cell size; a smaller cell gives more uniform power distribution and therefore more uniform absorption properties across the cell.

The outstanding advantages of the system are maximum response time, high optical density in the closed state, and good optical qualities.

The EOS report states that the Kerr cell shutter could be successfully integrated with the Army M65 Battery Commander's Telescope. Power to operate the electrical amplifier section would be available from the 28 volt vehicular power.

Baird Associates had also developed a Kerr cell device which was similar in operation to the EOS system (58). Four of these units were tested with animals during Operation Redwing (1956) but results were inconclusive because neither the protected nor the unprotected animals received burns. However, it was stated that the devices had small apertures (giving an extremely restricted field of view) and the open transmission was very low.

(2) The Stressed Plate Shutter

Following their research with the Kerr cell, Electro-Optical Systems developed another birefringence system, this time using solid-state materials (Pockel's effect) rather than a birefringent liquid. The system consists of Hayward C-3 glass plate mounted between a pair of Polaroid HN-22 filters. This assembly is bonded to a pair of horizontal tungsten carbide beams. Mounted vertically between the ends of the beams are stacks of piezoelectric ceramic wafers. When voltage is applied to the wafers and the glass is stressed, birefringence is induced. As with the Kerr cell, the Polaroids can be aligned in a fashion such that the device is normally-open or normally-closed when the voltage is off. Advantages over the Kerr cell include a lower operating voltage, feasibility of a larger aperture, increased open transmission, and less temperature sensitivity.

In the system tested during the 1962 weapons test (2) a bread-board model was operated as a camera shutter. That is, the polaroids were crossed and when no voltage was applied, the device was effectively closed. Operating voltage was about 7, 000 volts, closed density was 3. 0, and full closure was expected to be achieved in 100 μsec. Open transmission was intended to be 20%. The system would give repetitive operations and rapid opening times without re-arming or recharging. Prior to field testing, two experimental systems were bench tested in an Army laboratory. Open transmissions were 13 and 11% (rather than 20%) and closure times were 125 and 285μ sec (rather than 100μsec). The longer than expected closure times may either reflect peculiarities of the sensing/triggering units or the selection of materials for the shutter itself.

During the actual field tests, three of the triggering units functioned and nine failed. Therefore, it is difficult to evaluate the operation of the stressed-plate shutter itself. As is the case with other protective devices that require a separate sensing system to actuate a power supply, evaluation should be in two parts: the filter itself and the activating subsystem.

It should be noted that if the stressed plate shutter were to be operated in the configuration described above (voltage applied for the open state), failure of vehicular power would result in closure of the shutter.

Isomet Corporation has also done research on an electro-optical system, and their final report (163) includes a good theoretical discussion of the optics and construction of stressed plate shutters. In general, Isomet concluded that there were several technical obstacles to the construction of an acceptable all-purpose electro-optical shutter, the biggest shortcoming being a restricted field of view.

c. The ELF System (Explosive Light Filter)

The entire ELF System is a joint developmental effort of the Sandia Corporation, Omnitech Corporation, Bermite Saugus Powder Company, and Douglas Aircraft Company. The system consists of three functions; protective goggles, a thermal radiation shield, and an instrument lighting control. A silicon light sensor mounted on the flying helmet transmits a signal to an electronic control unit. The goggle system is first activated (described later), followed by activation of a folding thermal shield within the cockpit. Since it is assumed that the pilot may sustain some flash blindness before the goggle and shield are fully closed, the control unit also adjusts the instrument panel floodlights to maximum intensity in order to minimize flash blindness recovery time.

The goggle lens consists of a pair of transparent plates. When the electronic control system transmits a signal to the goggle unit, a detonating fuse is ignited, explosively driving a carbon colloid solution between the lenses and coating their interior surfaces. This effectively produces an optical density of 3 or more. To regain vision, the pilot unsnaps the occluded lens and replaces it with a fresh one. One of the major advantages of the system is the fact that open transmission is excellent (80%)(2).

The only time that the pilot is unprotected (assuming that the goggle works effectively) is the time during which he removes the occluded lens and replaces it with a clear one. Presumably the pilot would be protected by the thermal shield during this lens change-over.

The ELF goggle system has undergone a number of field tests including nuclear weapon test shots and flight testing. In the 1962 weapons test series (2), the goggles were integrated with 4 different triggering systems. Prior to the site tests, a bench test was made and closure was achieved in about 300μ sec. There were no blowouts or other hazards caused by the detonation of the explosive charge. In the test series (2), the primary evaluation was made of the triggering systems. The test weapons included both slow rise and rapid rise pulses, depending upon yield and detonation altitude. When the triggering units failed to operate, it was attributed to the fast rise time requirements of the trigger and slow rise time of the energy production.

The ELF system--protective goggles, cockpit canopy, instrument floodlighting, and a variety of sensors--has undergone a number of engineering developments since 1962. The system has been flight tested and approved, and limited production models will be available in the summer of 1965.

There are essentially two sensor approaches: the Omnitech sensor for the visible light and the General Electric sensor for the EMP. An improved sensor arrangement (146) utilizes a combination of three sensors and discriminating circuits, one sensitive to rapid rise time pulses and two which will respond to slow rise times. In addition, the signal discrimination of the sensors is such that accidental discharges will not occur due to sunlight reflections, landing lights, etc. Other changes have been made on helmet fitting. After being fitted with helmet, oxygen mask, and ELF goggle systems, visual perimeter readings were made for several pilots. Visual field measures through the ELF lens appeared to fall within the minimum configuration recommended by Parker (151). However, as Parker suggests, pilot acceptance ultimately determines allowable visual field restriction.

d. Photoreactive Devices

(1) Phototropism

A great deal of the present research and development work on countermeasure devices is centered on phototropic materials. Technically, phototropism is a property of a material whereby its spectral absorption characteristics change as a result of the absorption of photons. There are various organic and inorganic materials which change their spectral absorption characteristics after having absorbed radiation in the ultraviolet, visible, or infrared region (18). In the literature, there are a number of terms used to describe these spectral absorption changes: phototropism, photochromism, thermotropism, thermochromism, and metachromism. Photochromism is a phototropic reaction where absorption of the incident visible light photons produces a color change. Thermochromism is a spectral absorption change which occurs after thermal energy is absorbed. The literature on phototropism uses the term thermal energy synonymously with infrared energy. This convention has been adopted for the remainder of this section. Most of the reactions described in the literature are photochromic, so the terms photochromism and phototropism have come to be used interchangeably.

Photochemical processes have been defined by Noyes, et al. (140) to include:

(a) primary photochemical processes (which occur upon the absorption of a photon by a molecule, ending with the disappearance of that molecule or a change in its reactive state relative to the reactivity of similar adjacent molecules, all in thermal equilibrium),

(b) secondary photochemical reactions, and

(c) photophysical processes which do not yield a net chemical change.

By definition (140), phototropic reactions are reversible, and therefore satisfy the definition of a photophysical process. However, because most of the phototropic dye systems are subject to fatigue where some compounds undergo permanent chemical changes, there is a mixture of physical and chemical reactions. The Corning phototropic material described later appears to be the closest to a nonfatiguing material.

One of the reasons for including an explication of terminology in phototropic reactions is that some of the investigators use the terms loosely, or neglect to give full explanations about why terms with different meanings are used interchangeably. For example, one particular dye system may exhibit both photo- and thermotropic properties, with the phototropic reaction being more rapid and accounting for the greatest change in optical density. Unless this is explicitly stated, the reader may be confused to find that a photoreactive dye is activated by ultraviolet light one time and infrared energy another time. In another case, the investigators refer to photophysical and photochemical changes in the same dye system. This is interpreted to mean that the photophysical reactions of the dye account for its reversibility (the predominant reaction), but incipient photochemical changes may account for its slow fatigue.

(2) Mechanisms of Action

A phototropic system in the nonactivated state has a stable electronic configuration. However, when the system absorbs photons, there is an increase in the excitability of the molecules such that molecular twisting or photoionization may occur. The molecular mechanisms associated with vibrational or rotational twisting or photoionization include:

(a) isomerism,
(b) dissociation, or
(c) redox reactions (51),

Within these mechanisms. there are various molecular or submolecular phenomena (ring closure, color centers, F center electron trapping, etc.) which affect the optical configuration of the target species. The net result of this alteration of molecular configuration is a change in the spectral absorption characteristics.

There is a functional difference between basic mechanics of light response in phototropic and the magneto/electro-optical reactions described earlier. Both reactions call upon the re-orientation or reconfiguration of a molecule or (molecular complex) with the result that its spectral absorption properties are changed. With the phototropic materials, the incident light energy is the stimulus for a change in property. The magneto-electrical optical systems require an <u>auxiliary</u> source of power in order to produce the molecular reconfiguration. By analogy, the phototropic systems might be regarded as "active", while the electro-optical systems are "passive"

Phototropic reactions are all energy dependent. That is, the degree and speed of reaction is a direct function of the level <u>and</u> spectral distribution of the incident energy. Some of the phototropic enzyme, dye, or salt systems may only react to ultraviolet, others will only react to energy in a restricted portion of the visible spectrum, and still other reactions are thermal sensitive. Therefore, there are a great variety of approaches to the development of a light/thermal/phototropic system which will provide biological protection. Depending upon the materials used, the activating energy can be obtained directly from the fireball or can be obtained indirectly by an auxiliary activating system which is triggered by a fireball energy sensor. Reasons for direct versus indirect activation will be discussed later.

A second characteristic of some phototropic reactions which can sometimes be exploited in protective goggle design is reversibility of reaction. Once the incident energy has returned to normal levels, the materials will revert to the original clear state. If this reversal occurs very rapidly, the operator will not be required to make any manual changes, nor will the system require any deactivating circuitry.

One of the major advantages of a system which operates at the chemical, physical/chemical level is rapid reaction time. Reaction times of 5 μsec have been reported for some of the phototropic dye systems, while in theory they can react in nanosecond time (51).

(3) Polacoat Phototropic One-Way Filter

This system is a one-use, replaceable filter (87). The replaceable element is a plastic lens embedded with phototropic dyes. Prior to anticipation of a flash, the operator places the phototropic lens on a special, lightweight goggle which is already in place. Energy from the fireball darkens the filter, and the operator pulls the darkened lens off when the threat is no longer significant.

Original performance requirements were that the filter protect the eye against harmful effects in the spectrum range from 200 to 2,000 mμ. Forward action (darkening) of the material must be achieved in the low microsecond range, and final neutral density should be about four throughout the visible spectrum. The activated system (dark) should not be sensitive to temperature variations. The energy from the fireball must be able to activate the material after it passes through canopy material. Finally, open transmission and optical quality must be such that visual performance is not compromised during the inactive phase.

Some of the dye formulations tested by Polacoat were temperature sensitive. That is, an increased temperature slowed the forward reaction (darkening) rate in its later phases. Inasmuch as this material would be exposed to thermal energy from the fireball, a dye had to be selected which was either not temperature sensitive or was thermotropic (where an increase of temperature would speed the forward reaction).

Next, the material should exhibit "flip-flop" spectral absorption characteristics for the activating energy. This means that as the activating energy, near-UV in this case, darkened the materials, transmission of UV should increase. The reason for this is, if the phototropic material is visualized as being in hypothetical layers, each successive layer must be activated in order to achieve the fully closed state. Thus, UV must pass through the first opaque layer to activate the second layer, and so on. Naturally, the energy level of the incident UV will decrease in its passage through successive "layers", but enough layers must be activated to achieve a high net opacity.

The selected dye should have a high quantum yield: a large number of molecules reacting for each quantum of absorbed light. The dye should also have a high molar absorption coefficient (MAC) in the spectral region which is being filtered.

It is a property of many salt isomerism dyes that when ionized, they produce a color density rather than a neutral density. Inasmuch as a colored filter may pass energy at the far ends of the spectrum as well as in the colored region, Polacoat selected a dye which produced a purple-black response, and then added a permanent fixed filter to absorb the higher and lower wavelengths which were not absorbed by the activated dye. It was later found during dye selection experiments that the dye which produced the dark reaction was also reactive to visible and IR energy.

The salt isomerism phototropic dyes will return to the open or uncolored state upon cessation of the activating energy. However, it was found that some part of the reaction appeared to be chemical in nature, with the result that an equilibrium was reached before maximum darkening occurred. Therefore, it was decided to make the reaction irreversible by adding a bleaching agent. This agent keeps the material colorless in the absence of UV and absorbs products of the photochemical reaction (free radicals). Elimination of one of the reactants of the back (equilibrium) reaction thus speeded the forward reaction rate, and permitted maximum darkening.

Once the dye and bleaching agent were finally selected, a supporting material was found which was compatible with the phototropic dye. Various plastic media were tested to obtain one which had good optical quality, scratch resistance, flexibility, did not impair the phototropic reaction, and was stable during storage.

The total system has an open transmission of about 65% in the visible spectrum and about 0.01% transmission from 260 mμ to 2,500 mμ when activated. Reaction time measurements were made using photo-electric cells and an oscilloscope, and a strobe flash unit for a light source. A reaction time of less than 30 μsec was reported. The test report does not state what optical density was achieved in this time period (the full reaction, 1/e, 95% complete response, etc.).

This filter will darken upon exposure to direct sunlight; an optical density of 1 being reached in 35 sec, a density of 2.0 in about 80 sec, and full closure in 240 sec. When exposed to direct sunlight through aircraft plexiglass, it takes about a minute to reach a density of 1. (Ambient test temperature was about 16-17.5°C.) When exposed to daytime north light behind plexiglass, an optical density of 1 is reached in about two minutes. At nighttime (full moonlight), no change in optical density is noted over 300 minutes. The film will decompose* if it is exposed to an average value of 3.0 cal/cm^2/sec and it will also darken at elevated temperatures. The sensitivity of this material imposes some restrictions on usage. First, the material must be in a light-tight container when not in use. Second, the filter should be stored at reduced temperatures (35-40°F) if the storage period is extended (i.e., months). Finally, there is a limited period of time that the filter can be used during the daytime before the optical density becomes too great for critical vision. If the pilot were delivering a weapon while directly facing in the direction of the sun, or if there were pronounced specular reflections, the effective usage time for adequate vision could be well less than a minute.

Calculations were made by Polacoat to determine the effectiveness of

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*This problem of decomposition of a plastic supporting material and/or the phototropic coating is not unique to the Polacoat filter. In fact, decomposition temperature for the coating and the supporting material should be required for all test reports.

this goggle to protect against retinal burns at two slant ranges from nominal yield, air-ground missiles. These calculations used the energy/time profile of low yield weapons to determine if enough UV and/or thermal energy would be available at specified distances corresponding to weapon launch tactics to activate the goggles to an optical density closure of 4.0. The data used for estimation of the UV energy passing through the atmosphere (and the cockpit canopy) are based on conditions which may not be typical for all meteorological/geographical situations. It is possible, for example, that in areas where the moisture content is high and/or the canopy plexiglass absorbs UV, insufficient energy would be available to fully darken the dye.

The Polacoat report does state that greater control of the response could be obtained by using auxiliary light sources. They further state that insufficient information was available to determine the degree of flash blindness protection conferred by their filter goggle.

Polacoat tested two dye formulations for the one-way filter during weapons tests in 1962 (2). These phototropic dyes were tested at all stations, along with test animals. Some of the filters were directly exposed, and others were exposed behind plexiglass. Initial or open transmission varied roughly between 40 and 50%. These low value open transmission figures were probably due to the fact that the filters had been exposed to sunlight some seconds before test. No closure times were given; the evaluation was qualitative only. For medium yield weapons, lower altitude detonations, the film darkened at the same range where animal burns were produced in unprotected rabbits. A nominal yield warhead (low KT range) detonated at approximately two miles did produce rabbit burns at test stations where the film did not darken. A low megaton yield detonated at an altitude of several miles served to activate the phototropic material at a range where retinal burns were produced in unprotected animals.

(4) The Dynacell (Polacoat)

Extending the results of their research on phototropic dyes, Polacoat devised a phototropic goggle concept which is self-clearing (111). In this system, a phototropic dye solution is run through a thin-walled optical cell. The color reaction itself is irreversible, but fresh, unactivated dye will flow through the lens flushing out the activated dye. The clearing time can be varied by adjusting the flow rate. Because the fluid is being constantly replaced, it is possible to use a very sensitive dye formulation and even if the dye were to be activated by sunlight, it would be replaced immediately. It is stated that these dyes can achieve an optical density of 4 in the lower microsecond range (less than 50 μsec). A fixed filter is added to exclude any wavelengths passed by the phototropic dye. With a 300 cc reservoir of inactivated dye, it is calculated that the system is able to operate for about two to three hours under daylight conditions.

At extended distances from a detonation, there is a problem of receiving enough energy on directly activated materials to achieve an optical density high enough to confer positive protection. Therefore, Polacoat has tested a system where a focusing lens is placed in front of the filter such that incident energy is focused on the plane of the filter. Thus, the concentration of the activating energy per unit area is at the plane of the phototropic material. The calculations presented to show the effectiveness of this system indicate that when the incident energy level is sufficient to produce an optical density of 4, the total thermal energy per unit area on the retina would be 0.00096 cal/cm^2 (which is well below burn threshold).

Although not stated in the report, it is assumed that unless the focusing lens were made from a UV transparent material, the activating energy reaching the filter would have to be visible and thermal, not UV. These dye systems do have thermotropic and photochemical properties, but it is not specified if these latter types of activation would produce as rapid a reaction or if the final color would be the same as that produced by UV activation.

There are some aspects of a system such as this which could limit its application. The first consideration is a logistical one. The phototropic dye system has limited stability and should be mixed just prior to use. This is not a major problem, but it is one more item of preparation which would have to be accomplished before each mission. Second, if the optical focusing system is used, it would restrict the field of vision. However, when used on an optical aiming or sighting device, this consideration would not be important. Third, it might be too bulky for easy hook-up in a crowded aircraft cockpit and for compatibility with various flying helmets.

Prime advantages of the concept are direct activation, rapid reaction time, high optical density (in the closed state), automatic lens clearing, and uniform response regardless of distance. In addition, because of the non-selective nature of the dye (in reference to activating energy), it could be activated by any intense light source including specular reflections or direct sunlight. Inasmuch as reflections from the fireball or sunlight can produce detrimental eye effects. a nonselective reaction could be advantageous, providing that the operator would not be bothered with occasional, temporary activations.

Polacoat has recently completed work on a directly-activated, photo-thermosensitive windshield segment. The system is similar in operation to the Dynacell; the windshield is a thin cell through which flows the photosensitive dye. The dye reservoir holds sufficient fluid for three hours of continuous use under normal sunlight conditions.

Open transmission is 70% in the visible region; activation (darkening) begins within 50 μsec, achieving an optical density of 4.0. Re-opening time is less than 5 sec.

The Polacoat devices are currently being tested at Wright-Patterson Air Force Base. *

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*We are grateful to Polacoat, Inc., for providing us with a complete summary of their developmental work in eye protective systems.

(5) VADO and Materials by Marks Polarized Corporation

Marks is working on a variety of photoreactive materials, including the VADO (variable optical density) film. The VADO film is a polymeric material using copper or transition metal halides in combination with catalytic agents such as phosphoric acid. The material can be coated on a transparent supporting medium such as lenses or a cockpit canopy. Open transmission to light in the visible spectrum is better than 50%, and optical densities of 3.5 or more can be obtained in the microsecond range. Upon cessation of the activating energy, the material returns to an optical density of 2.0 in less than 10 sec, and full recovery is achieved in about one minute. An incident energy of about 0.1 cal/cm^2/sec will produce full opacity, and there is no reaction to an energy level of about 0.004 cal/cm^2/sec.

It is a property of the VADO material that its electrical resistance decreases when it is illuminated, and increases when there is no ambient light. This property could be used to trigger a secondary activating source or the stimulus for clearing.

Reversal of the material is a function of humidity; complete reversal will occur when the relative humidity is greater than 50%. At high humidities (90%), reversal can be accomplished in several seconds.

VADO is UV, visible, and IR sensitive. Recent advances have been made with the VADO material so that it may be cycled up to 75 times, the shelf life has been increased, and it can withstand surface temperatures of 5.0 cal/cm^2 without decomposition. This high thermal resistance is a feature unique to the Marks' VADO materials.

Marks has also developed a dipole shutter material. This is a liquid medium in which small dipolar crystals are suspended. Under the influence of an electrical field, these crystals will orient themselves parallel to the line of sight, and the material is in the "open" or transparent state. When the field is returned to a ground state, the crystals become randomly oriented due to brownian motion, and the material becomes reflective.

Marks has also worked with an electro-optical system using ADP (ammonium dehydrogen phosphate) crystals. *

(6) Midwest Research Institute

M. R. I. has an experimental program to develop and test various darkening materials which can be used for eye protective systems. Their first progress report (131) includes tests on different formulations or preparation techniques of oxide films (zinc oxide/gold and cadmium oxide), syndone compounds (N-3-pyridyl syndone), and ultraviolet absorbing semiconductor materials.

e. Indirectly-Activated Phototropic Devices

A position currently held by several developers of eye protection devices is that although it would be ideal to have the phototropic material activated directly by the incident fireball energy, there are too many intervening variables to insure reliable activation of the material. Therefore, one development trend for present-generation devices is to use an indirect source of light to darken the material. Basically, the principle is simple: a light/thermal sensor detects the rapid energy rise from the developing fireball. A special discriminating circuit distinguishes this pulse as being different from normal ambient energy and triggers the discharge of a special auxiliary light which is focused on the phototropic material. The energy output of the auxiliary source can be selected to correspond to the maximum sensitivity of the dye formulation being used. Other advantages of indirect activation include a uniformly distributed response, achievement of full optical density regardless of the distance from the fireball, and not having to depend on UV energy from the fireball.

With this method, the principal problem is to devise a sensing/trig-

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*Information obtained from reference (151) and discussion with Mr. Charles Bersch, Bureau of Naval Weapons.

gering system which will respond to various pulse characteristics and will trigger the system at any distance where the fireball energy is potentially hazardous. Next, a power supply must be provided to activate the auxiliary lighting source. The goggle unit itself becomes more complicated and bulky because of the addition of filters, reflecting surfaces, flash tubes, etc. Finally, the system in its final form is a complex piece of equipment with attendant maintenance and reliability problems.

(1) NCR, EG&G Indirectly-Activated Phototropic Filter

National Cash Register (NCR) and Edgerton, Germeshausen, and Grier (EG&G) have worked together for several years to develop such a system. NCR worked on the dye material, while EG&G developed the goggle system to utilize the dye. The original NCR/EG&G goggle system was designed to give eye protection against the detonation of the low yield GAM-83B missile (183).

In order to define the operating requirements for eye protection, an analysis was performed to specify the pulse characteristics of the missile warheads and to determine the biological thresholds for burns and flash blindness. The first calculations showed that there would not be sufficient energy reaching the filter to directly activate the phototropic material to an optical density of 2.0 or more. In fact, it was calculated that in order to be directly activated under the following conditions:

a small warhead (with short rise time pulse),
a slant range of about four miles, and
attenuation from the atmosphere and the canopy materials,

the phototropic material (NCR's P136) would have to be 40-170 times more sensitive than it is at present. This was given as sufficient reason to resort to an indirect activating system.

Next, a requirement for closure time of less than 100 μsec was established on the basis of an analysis which revealed that the amount of energy released during the first pulse was sufficient to produce retinal burns. The author made the point that in many estimates of retinal burn hazard, investigators have neglected to take the first pulse into account.

In order not to exceed a two-second recovery time from the flash blindness (on the assumption that some energy will enter the eye), the optical density would have to be increasing past 2.0 at 100 μsec to 3.0 for the time remaining between 100 μsec and the first blink at 100 millisec. In fact, however, experimental test evidence shows that most of the density can be obtained by 50 μsec.

The photochromic material when activated did not absorb evenly throughout the spectrum; there was a light leak in the 460 mμ blue region and another leak beyond 660 mμ on into the IR region. Therefore, two fixed filters were added; one to absorb in the blue, and the second to absorb in the IR range. The result was a filter with an open transmission of 40% in the visible region.

The configuration of the present goggle design is basically as follows: xenon flash tubes are placed horizontally above and below the photochromic liquid to expose the dye. The dye is suspended between two quartz wedges such that the energy from the flash tubes is reflected and distributed evenly across the surface of the dye. The arrangement of the fixed filters stops most of the UV activation energy from impinging on the eye surface.

EG&G has continued its experimental program, and significant advances have been made over the 1961 system. Open transmission is 35%, full closure is 3.6 optical density, achieved in 75 μsec. Clearing time for useful vision is about two seconds. A conservative estimate on number of operating cycles is 30-50. Optical quality of the open lens is very good. The power pack (using aircraft power) weighs 22-1/2 lbs and delivers 600 joules of energy to the lens for darkening. Storage stability seems good, dye materials have been stored in a dark bottle for over a year, with no effect on density or activation time. There is a negligible reaction of the dye to ambient sunlight because of the sideband filter at the front of the goggle.

EG&G is now doing engineering production work to have the goggle meet the various MIL-Spec operating requirements and production models will be available in 1965. This work is being done for the Bureau of Naval Weapons. The operational goggle, using a liquid dye cell rather than coatings, has the entire filter as a replaceable element (after some 50 operations) for the cockpit environment. The element can also be recharged with new dye in a forward supply area.

EG&G is also working with Frankford Arsenal to continue development of a periscope protective filter system. Prototype periscope systems are available now which are similar in basic design to the goggle system. It is predicted that within several years' time they will be able to produce a filter which is clear in the open state. This dye will reach a density of about 2.3 to 2.5. In two years they expect to achieve a closed density of 3.0.

The 1961 goggle system was tested in the 1962 weapon test series under a variety of detonation conditions. Observations were made primarily to see if the sensing/triggering system would operate with different weapon rise times and energy levels. No measures of closure time or closed density were given. The indirectly actuated phototropic goggles triggered more often than any of the other tested devices. The different test stations were located at distances up to 55 miles from the fireball and weapon yields were from the low kiloton to the low megaton range. Burst altitudes ranged from low altitude to upper atmosphere. Because of the variety of conditions under which the systems were successfully triggered, the tests were considered to be comprehensive (2).

f. Indirect Viewing Techniques

The indirect viewing technique is a foolproof method which potentially may provide continuous, predictable, and effective protection against harmful eye effects. However, this approach is limited to only a few applications. The prime advantage of the indirect viewing technique is that the image intensity on the viewing screen never exceeds a pre-set level. The principal disadvantages are limited resolution, reduced depth of field, restriction of visual angle, equipment vulnerability, and power requirements.

The image converter, an indirect viewing device, is similar in basic principle to television. It is an electro-optical device which converts light energy from a source into an electronic image, which in turn is focused on a fluorescent screen. The image of the light source is focused by a lens onto a photo-cathode. Electrons emitted from the excited photo-cathode are accelerated to the screen, producing the image. The fluorescent image has the advantage that its maximum intensity is a function of the converter system, not the intensity of the image source. A modification of this approach is to use a solid-state converter, but this has both advantages and disadvantages when compared with a tube converter. Perhaps the most serious limitation to present generation solid-state converters is resolution (173).

Hughes, Convair, and General Dynamics have each developed image converter systems (151, 173), some of these being ingenious examples of packaging an electronic image system into a compact unit.

No detailed descriptions of optical quality were available for this report, but one research report (173) does mention the problems of resolution, reduced depth of field, and restricted viewing angle. Despite these disadvantages, the indirect image approach [including the iconoscope (122)] may find use in specific application such as visually guided weapons.

D. New Developments

Many of the devices or approaches described previously are in development or feasibility stages, especially the photochromic systems, so it is somewhat arbitrary to make a distinction between old and new developments. There are, however, some newer approaches or techniques which may offer some desirable features.

The first is a reversible electroplating technique advanced by Zaromb Research Corporation. They are currently doing a feasibility study to see if large areas, such as windows, can be occluded. A second body of research is concerned with dye enzyme systems in photochromic compounds. Some of this work is being done at the Materials Laboratory, Wright-Patterson Air Force Base. Unfortunately, detailed descriptions of these approaches could not be obtained from the respective investigators.

There is another material which has recently been developed by Corning Glass Works (39). As mentioned earlier, an ideal material would have the following properties: rapid closing time, high optical density in the closed state, rapid clearing time, sensitivity, chemical stability, and the potential for repeated cycling without fatigue, and high transmission in the open state.

The new photochromic glass developed by Corning Glass Works (177) has many of these properties. This material consists of photosensitive, submicroscopic silver halide crystals precipitated in glass. When the material containing silver chloride is exposed to UV, the crystals darken just as they do in a photographic emulsion. However, when the UV is withdrawn and visible or thermal energy is applied, bleaching will occur. Glass of this type has been put through thousands of cycles with no degradation of performance. The reason given for this reversibility is that because the submicroscopic crystals are embedded in an inert medium it prevents the color centers from diffusing away, growing into stabile silver particles, or reacting chemically to produce an irreversible decomposition of silver halide.

The photochromic properties (reaction times, spectral characteristics, etc.) can be varied by using different crystal compounds combined with different heat treatments used in the formation of the glass. The color that is produced absorbs in the visible region and in the near UV and IR. The open transmission of photochromic glass is essentially that of window glass, and optical densities of 2 have been obtained in quarter-inch thick glass exposed to sunlight. However, reversal was slow.

With an exposure stimulus in the microwatt/cm^2 range, a mineral light (UV) placed one inch away from the glass brings the transmission down to 33 1/2%. A one-millisecond flash from a 40 watt-sec flash gun decreases transmission to 25% of the original value (39). Response time for some of the materials has been as low as 1 millisec for full closure.

It is obvious that the small change in optical density and slow clearing rate are limitations in the present formulations. However, the stability and nonfatiguing characteristics of photochromic glass are very desirable features. If a theoretical capability can be demonstrated for achievement of higher optical densities and more rapid activation and clearing, these materials would have great potential for flash and burn protection.

Marks Polarized Corporation is also continuing work on darkening materials, including further work on the dipole shutter. Notable advances include increased cycling capability, chemical stability, and thermal resistance over earlier materials. This work is being supported by the Navy and the Air Force.

EG&G is continuing developmental work on filter systems which are adaptable to submarine periscopes, as well as pursuing research on new dye systems. It is possible that 50% open transmission in the photochromic filter can be achieved in a year or so.

General Electric Company (Military Communications Division) has a production model EMP sensor system which is being tested by the Navy and Frankford Arsenal. In addition, they are working on an advanced shutter concept for the Air Force, utilizing a reversible photoplastic material.

National Cash Register (NCR) is in the process of testing a 6 by 8 inch windshield segment which operates on the same principle as the NCR goggle system. Following evaluation of the laboratory model, a prototype unit may be flight tested in early-1966. The windshield segment has 41% open transmission in the visible range, achieves an optical density of about 2 in 140 μsec, and clears in about 2 sec. NCR (Military Division) is also exploring the possibility of adapting a prototype photochromic filter to a VIDICON TV system; the purpose being to protect the TV system from the intense energy pulse.

Bausch and Lomb, Inc., has developed a periscope shutter system for the Army Tank-Automative Center. The unit is indirectly activated and irreversible. Operating characteristics are not available for an unclassified report.

TRW Space Technology Laboratories (Redondo Beach, California) is continuing basic research for the Air Force on triplet states of organic molecules. These compounds can be incorporated into some transparent plastics, and will darken upon exposure to light. Response time is very rapid, optical densities of about 2.0 can be obtained, and recovery time varies between microseconds and seconds. Some of these photochromic materials have been subjected to 700 flashes without evidence of fatigue.

This is a cursory review of past and present research in the development or production of countermeasure systems. Undoubtedly some other development efforts have not been included, but these possible oversights are not intentional. The following listing of current or pending research contracts on eye protective systems or materials is included as a source for further information.

1. <u>Research and Reports on Photochromic Materials (Triplet State)</u>

   TRW Space Technology Laboratories, Redondo Beach, California. Supported by AF41(609)-1457, AF33(657)-11708, AF41(609)-2425, School of Aerospace Medicine.

2. <u>Research and Reports on Photochromic Materials (Spiropyrans)</u>

The National Cash Register Company, Dayton, Ohio. Supported by AF41(609)-2292, AF41(657)-215, AF41(657)-322, School of Aerospace Medicine.

3. Evaluate Triplet State Materials

American Cyanamid Company, Stamford, Connecticut. Purchase Request AM-4-10174 (Air Force, Aerospace Medical Division).

4. Research and Reports on Flash Blindness Phenomena and Design Criteria for Triggering Devices

Technology, Inc., Dayton, Ohio. Supported by AF33(657)-11557. Aerospace Medical Division, Brooks Air Force Base. AF41(609)-2464.

5. Research on Flash Blindness Protective Device (Solid-State Image Converter)

General Dynamics/Pomona, California, Supported by U.S. Army Natick Laboratories, RFQ AMC(X)19-129-64-663MQ.

6. Study and Application of a Solid-State Viewing Device for Suppression of Flash Blindness and Retinal Burn Control

Bausch and Lomb, Inc., Rochester, New York. Supported under Contract DA-30-069-AMC-441(T).

7. Study on Certain Tenebrific Materials

Nuclear Research Association, Long Island City, Long Island, New York. Bureau of Naval Weapons Synopsis No. 377-64.

8. Spectroscopic Investigation of Photo- and Thermochromism

University of Houston, Houston, Texas. Supported by AF33(615)-1733.

9. Reversible Electroplating Technique for Light Modulation

Zaromb Research Corporation, Passaic, New Jersey, Joint Contract with U.S. Army Natick Laboratories and Naval Applied Science Laboratory.

10. Research and Development on the Indirectly Activated Photochromic Goggle System

    Edgerton, Germeshausen, and Grier, Inc., Bedford, Massachusetts. Supported by Bureau of Naval Weapons.

11. Research and Development on Periscope Anti-flash System

    Edgerton, Germeshausen, and Grier, Inc. Supported by U. S. Army, Frankford Arsenal.

12. Research on Acid-Base Characteristics of Phototropism

    Hughes Aircraft Company, Hughes Research Laboratories, Malibu, California. Supported by U. S. Air Force, Office of Aerospace Research. Contract No. AF49(638)-1264.

E. Evaluation Criteria for Countermeasure Devices

Developing a comprehensive and useful set of evaluation criteria for eye protective systems mirrors most of the problems involved in the study of flash blindness and burns plus the problems of designing acceptable and practical equipment for field use.

The equipment designer works from two sets of specifications: requirements and technological capabilities (state-of-the-art). In cases where one of these is well defined or well advanced, research and development can work "in one direction". However, when the technology is relatively unexplored and when the requirements are uncertain, the process of making trade-offs and compromises is complex. Such is the case with eye protective systems. As a result, the devices that have appeared so far may satisfy only a portion of the requirements for the diverse prospective applications. This does not imply that all present devices are inadequate, it is simply that they still must be regarded as interim measures or as an indication of the feasibility of a particular approach.

As a piece of hardware is being developed, or its feasibility being shown, it usually becomes apparent that the device does not completely meet expectations. At this point, the users and developers legitimately re-examine the requirements to see what sort of realistic compromises can be made. Or, they ask how realistic the requirements are. For example, Corkhill (38) questions the absolute necessity for low microsecond closure times and a requirement for optical densities of 4 or more. Undoubtedly if, on the basis of additional biological findings, more realistic criteria can be set for particular missions, the development task may be considerably less difficult.* At the present time, Bio-Technology (Arlington, Virginia), General Electric (Oklahoma City, Oklahoma), and Technology, Inc. (Dayton, Ohio) are working on flash blindness prediction models. The function of these models is similar to that of the burn models: analysis of the variables involved in energy production, transmission, and absorption, for the purpose of estimating the requirements for protection.

The most stringent requirement is, of course, for biological protection. To evaluate the potential biological effectiveness of a device, it is a matter of comparing the operating characteristics of the eye filter with the characteristics of the threat, using as a reference point, threshold effects for the eye. Following this analysis, the device is examined for its compatibility with mission performance and environment. Finally, the system is examined on the basis of reliability, logistical support requirements, cost-effectiveness, user acceptance, and so on. With any system less than ideal, a further evaluation analysis becomes necessary and poses such questions as: "how much would the mission be compromised if the wearer were to be flash blinded for x seconds?", or "under the stated conditions, what is the probability that the operator will actually 'see' the flash?" In fact, it might be worthwhile to let the operations and missions groups make the decision to use a particular device rather than waiting for a precise definition of requirements to emerge from research groups.

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*The Air Force move from the 1% to the 2% (transmission) gold visor at least partially reflects this recognition of setting more realistic criteria.

In the realm of training and simulation, Bio-Technology has developed flash blindness simulators for use in Naval air training. Pilots and pilot trainees will have the opportunity to experience flash blindness and understand the significance of visual recovery relative to performance of critical visual tasks. Further, eye protective systems can be used during these training sessions to give pilots confidence in their protective gear.

The following outline summarizes the variables and critical questions for evaluation of a particular device.

1. Biological Information

a. What are the thresholds for foveal and parafoveal retinal burns for the full spectrum of pulse types, integrated energy levels, spectral distributions, and image sizes on the retina? These data must include individual variability as well.

b. What are the similar thresholds for various degrees of flash blindness under the same range of conditions as above?

2. Operating Characteristics of the Device

What are the optical density and spectral absorption characteristics of the device relative to incident and threshold energy levels. On dynamic devices this comparison is complicated by considering:

a. the time lapse between the first appearance of the flash and the initiation of closure,

b. the density closure rate relative to the growth rate of the pulse,

c. the final density,

d. the duration of closure with respect to the duration of hazardous energy levels.

There has been a considerable amount of work performed and compiled to supply the complete range of data on description of the energy pulse(s) from different yield weapons detonated at different altitudes. Examples of such reports are references 2, 3, 38, 153 and 83.. The quality of the data is improving (due to better measurement and analysis techniques) but the data are still difficult to obtain and interpret despite a significant effort within certain government agencies to make it more readily available. Some of the data used by development organizations to establish requirements show marked inconsistencies, and unfortunately the evaluation of their particular device sometimes was based on these poor data. Atmospheric attenuation alone is a factor which plays a tremendous role in estimating hazard parameters for weapon detonation. Some scaling laws are also often misleading, to the point where requirements based on the extrapolation of scaled values could be totally unrealistic.

Second, there are still gaps in the information about biological thresholds. There are too few data from animal and human exposures during weapons tests. Thus, thresholds have been based on laboratory use of nuclear pulse simulators with the assumption that the artificial pulse bears close enough semblance to the real pulse to provide valid quantitative information.

Third, the descriptions of operation for some of the dynamic devices are theoretical estimates or are based on bread-board tests. Closure time is a prime example here. The time course of closure (on dynamic devices) must be described both as a function of incident energy and geometrically. For example, the ELF goggle system closes vertically like a curtain, the electromechanical shutter closes laterally, and the phototropic materials darken at a nonlinear rate. Further, with the molecular devices, the character of the increasing density varies with temperature, stability of the reactive materials, number of prior activations, time after the last activation, and character of the activating energy. Closure must therefore be quantitatively defined under all ambient conditions.

Development and testing of sensing/triggering systems for indirectly activated dynamic systems remains a problem. In order to avoid spurious discharges due to sunlight, reflections, landing lights, etc., various discriminating circuits are used which only respond to a light pulse with certain characteristics. In the past, a number of the device failures have been the fault of the trigger discrimination; typically, a slow rise detonation pulse would not trigger a fast rise discriminator.

National Cash Register (33), a firm which has been working on both development and field testing since 1958, has designed and fabricated two laboratory systems for testing and evaluating eye protection systems (33). The first item is a first pulse simulator (138) which can be used to evaluate light sensitive, rate discriminating triggers and flash sensors. Peak irradiance range is 0 to 10 watts/cm^2 at 50 cm from the source. Rise to peak time is adjustable to 25, 100, and 400 μsec. The Xenon flash tube delivers 40% of its radiation in the UV and blue spectrum. The second system (137) is an optical test bench used for measuring the response of dynamic devices. A light source or the First Pulse Simulator can supply the test energy which is focused on the device. The emergent light is focused on a photo detector, the output of which can be supplied to an oscilloscope where a scope camera is used to record filter density versus time. Closure time measurements can be made as low as 5 μsec $\pm$ 2 for 300 to 700 mμ energy and 300 μsec $\pm$ 10 for the outputs in the spectral region 700 to 2, 500 mμ. In addition, the test chamber can be environment controlled for temperature and haze.

Sources for triggering, not previously described in this section, which have been suggested include the Teller light and the electromagnetic pulse. There is a brief description of these phenomena in a preceding section.

3. Operation Constraints

After evolving an estimation of biological effectiveness, the protective system is then evaluated on the basis of its practicality for field use and its compatibility with performance of the mission. The first two considerations are open transmission and field of vision. Many of the devices have a low open transmission. In the daytime this may not be serious but at night visual requirements are usually far more stringent. It has been suggested that an all-purpose eye filter for day and night use would require an open transmission of 85% or better, However, it may not be practical to wait for such an ideal open transmission if other operating characteristics are acceptable.

Field of vision is a prime requirement for just about any mission application, except in the special case of optical sighting and aiming instruments. Parker (151) has examined phases of the mission profile for the Navy A4D in order to obtain an approximation of visual field requirements during each phase. These data establish visual perimeter requirements for a protective goggle. This type of analysis would eventually be necessary for a variety of missions if visually restricting devices are to be used.

Optical quality is also important, especially for reconnaissance and aiming.

During the earlier technical descriptions, remarks were included on special problems of logistics and compatibility with other protective gear. Added to this are problems of reliability, shelf-life and storage requirements, fitting, maintenance, servicing and calibration, weight, power requirements, susceptibility to environmental extremes, and so on.

4. Probability of Mission Failure Due to Temporary Incapacitation

None of the more generalized systems affords complete protection against all eye effects, especially flash blindness. Therefore, a reasonable question is: if protection is incomplete, for how long can flash blindness be tolerated? From the mission standpoint, a general range of tolerable vision loss can be estimated for some mission phases, but this time period approaches zero for such critical phases (in flying) as take-off, landing, low level, high speed missions, aerial combat, instrument flying in turbulence, refueling, and some types of weapon delivery. From the other standpoint--trying to predict the degree of flash blindness or how long flash blindness will preclude useful vision--this is subject to so many variables that it would be extremely difficult to determine. However, considerations are being given to methods which reduce recovery time or aid information-gathering during flash blindness, such as floodlighting the instruments or using another sensory input channel.

The problem of performing visually controlled tasks during the period when goggles are actuated must also be considered. How long will it take for the device to return to an effective open state or how long will it take to remove an occluded one-way filter? The basis for application of one-way dynamic devices is centered on the assumption that the time and place of detonation can be predicted and that the operator will have time to reopen the device before vehicular control is lost. This assumption will have to be verified during simulated missions.

F. Summary

At their present level of capability none of the anti-flash systems satisfy all mission requirements. As examples, the Kerr cell with its rapid activation time is compromised by having a small aperture and low open transmission. The one-way, directly activated goggle may have the potential for rapid closure and high density, but it is questionable if for all injurious conditions there will be sufficient energy to trigger it. Also, it can be worn only for short periods of time during the day. The ELF system has desirable open and closed transmission properties, but closure time may not be rapid enough for fast rise pulses. The EGG/NRC indirectly activated phototropic filter combines a greater number of desirable features (for all-purpose vehicular use) but open transmission remains as a problem. The Dynacell also has excellent dynamic characteristics, but imposes restrictions on wide angle vision. The indirect-viewing techniques would give adequate protection under any circumstance, but impose significant constraints on visual field, depth, and resolution.

For the foot soldier or civilian, the fixed density filter is the best compromise, but only for daytime use. However, there is certainly room for improvement of UV and IR removal standards for civilian sunglasses. If significant advances are made with phototropic glass, the entire protective field could be altered, both for military and civilian usage.

It would also be worthwhile to re-examine the feasibility of using the louvered, eye-slit devices.

Despite these problems inherent in each of the devices described here, some have shown a sufficient number of desirable characteristics to warrant interim adoption for selected operational purposes. These include the 2% gold visor, * the monocular eye patch, the ELF goggle system, and the EG&G photochromic goggle and periscope systems.

No report references have been found for work by NATO countries or the Soviet Union on their respective work for flash blindness and burn protection.

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*2.0% transmission for the Air Force visor, and 2.75% transmission for the Navy visor.

IX. SIGNIFICANCE OF THE THREAT

A. Introduction

What is the significance of the flash blindness and chorioretinal burn threat to civilian and military operations? The military and civilian agencies concerned with threat assessment must determine which groups of personnel are most likely to be exposed, what types of missions are most vulnerable to failure because of impairment of the operator's vision, and what percentage of a large population group would be likely to sustain some degree of photostress?

Earlier, the significance of flash blindness and chorioretinal burns was discussed from the biological standpoint. For example, visual performance following receipt of a burn will ultimately depend upon the size of the lesion and its location. Initially, however, the individual who is exposed to sufficient energy to sustain an ocular burn will also experience flash blindness to a degree which could seriously interfere with the immediate performance of visual tasks. The section dealing with flash blindness provides ample data to show that the individual may lose effective vision for several minutes following exposure to an intense, diffuse source. The significance of this temporary impairment of vision can only be determined by analysis of the tasks being performed when flash blindness occurs. The section on countermeasures discusses some of the problems associated with the protective systems: restrictions in visual field, reduced open light transmission, requirement for the operator to perform manual operations, reaction time characteristics of dynamic devices, and the probability of device failure. Consideration of all these factors must be made in determining the operational significance of visual impairment.

To date, several million dollars have been spent to define biological effects or to develop countermeasure devices, but much less research has been directed toward making operational assessments of the visual threat.

Detonation of moderate to large yield nuclear weapons at high altitude may produce a permanent visual scotoma in all people oriented such that the fireball occurs within their field of view. Unless the burst is obscured by clouds or haze, any person within line of sight is a potential victim. Blink reflex behavior is ineffective for protection against high altitude bursts. Flash blindness may be produced in individuals not oriented towards the fireball, and even specular reflections may possibly produce permanent scotomas. Detonation of the same weapon at a lower altitude within the atmosphere is less of a chorioretinal burn hazard only if people do not reflexively or consciously look at the fireball. The number of potential victims is less for lower atmospheric bursts, but the injury rate among those within a given radius will depend to a large degree on the absence or presence of maladaptive responses.

B. Significance of the Threat for Civilian Groups

The fact that there was only one case of retinal damage among the survivors of Hiroshima and Nagasaki has for many years been cited as evidence that this threat was insignificant in comparison to other problems. However, the threat must be reassessed in view of the much longer persistence of multi-megaton fireballs at lower altitudes, and the tremendous damaging potential of high altitude detonations. At Hiroshima or Nagasaki, a person facing in the wrong direction could not react fast enough to turn around and fixate on the fireball before the emission rate had decayed to a non-hazardous level. The range at which persons can be injured by looking directly at the fireball was limited at Hiroshima because of three factors: it was a bright sunny morning and exposed people would probably have had constricted pupils, the burst altitude and atmospheric attenuation restricted the number of potential victims to those within 10 to 20 miles, the pulse characteristics of the particular weapon were such that a blink reflex could protect an individual from the most hazardous phase of fireball growth. If a 10 megaton weapon had been used under similar circumstances, the period during which retinal damage can be produced would be 15 to 20 times as long. At night the range at which damage may be sustained may be 2 to 3 times as great due to dilation of the pupil. Higher altitude bursts extend the area over which the fireball is visible and may reduce the effects of atmospheric attenuation in certain conditions. In short, it is not completely valid to project the present-day nuclear threat to civilian populations on the basis of the low yield weapons used in 1945. The most significant factor for threat assessment is that there is a low probability that people would be looking up at the sky. However, even this has a limitation in view of the longer pulse duration of strategic weapons. The fireball of a strategic weapon detonated within the atmosphere persists for a sufficient duration to attract attention, allow for orienting behavior and fixation, and several eye blinks. Conversely, there would be time for the trained individual to initiate protective action (blink and look away) which could save him from serious eye effects. Because neither of these possibilities has been explored, it is not possible to make a reasonable assessment of the photostress threat to the civilian populous. These appear to be the most crucial questions. Among the classes of civilian activities, vehicle operators and controllers and surveillance personnel are the most vulnerable and sensitive to loss or impairment of vision. While the high density, commuter traffic scene potentially provides the greatest number of injuries resulting from transient or sustained visual impairment, the natural obstructions such as surrounding buildings and automobile roof, together with atmospheric haze might serve to significantly reduce the incidence of impairment.

From the standpoint of long-term support and rehabilitation, a large number of severe bilateral retinal burn cases could add appreciably to the problems of post-attack recovery in the social and economic areas. Also, behavioral problems associated with individual or mass visual impairment cannot be predicted with assurance. Perhaps the most important research question about the visual threat to civilian population concerns the factors in casualty prediction. Prominent here is the question of human orienting behavior. It is necessary to answer the following types of questions. What is the natural reaction to an intense light stimulus? Orienting and fixation? Can the individual be educated and/or trained to avoid such orienting behavior if it in fact does occur? At present, there is only scant information about these critical behavioral characteristics.

C. Significance of the Threat for Military Groups

By nature of their occupation, military personnel are likely to be in the vicinity of nuclear detonations. Although preparedness may be at a higher level than for civilians, the consequences of even short-term transient visual impairment can be greater. Military pilots and weapons directors have been singled out as recipients of countermeasure devices on the basis of high probability of exposure, and dependence of mission success on visual continuity.

Flash blindness has been assumed to be the more significant of the two forms of threat because the emphasis has mainly been on aircraft control. However, for the military as a whole, retinal burns probably pose a greater total hazard because virtually all combat and defensive operations require "good" visual performance over extended periods of time. The civilian may be in a flexible enough work environment to adjust his job to a mildly impaired visual capability, but the soldier, gunner, or tank driver cannot perform effectively with bilateral foveal lesions.

Relatively little research has been done in the real or simulated mission environment (aircraft, ground vehicle, weapon aiming, etc.) to obtain empirical data on mission safety or performance after flash blindness. A major exception are the studies conducted by personnel from the U.S. Naval Air Development Center. The first study (94) was to determine the degree of ability of pilots to continue a flight maneuver when blinded for periods up to 15 seconds. The time that the aircraft was safely maintained by the blinded pilot was judged by a check pilot. The attitudes ranged from straight and level to the 180 degree point of a slow roll. The tested pilots had no trouble maintaining straight and level flight at high or low altitudes for periods up to 15 seconds, at which time the experiment was terminated. Blinded pilots could safely maintain inverted flight for about 5 seconds. Other attitudes were of intermediate difficulty compared to the two mentioned here. The results of the second study (28a) were essentially similar. The authors recommend that pilots have the opportunity for training in the methods to regain vision should flash blindness occur.

In contrast to the majority of flash blindness studies where absolute measures of acuity and threshold are measured, less work has been done on recovery characteristics in an operational context where the subject is familiar with the test objects. As an example, in some instrument reading it is only necessary that the operator know the relative position of an indicator. Acute vision may not be necessary to retain gross control.

Bio-Technology, Inc. (Arlington, Virginia) will be delivering flash training consoles to the Navy this year, and this type of training should provide valuable information on visual recovery characteristics for operational tasks. The A. F. School of Aerospace Medicine is also conducting flash blindness studies in a simulated operational environment, and some results should be available in 1965.

Undoubtedly, operator training under flash conditions would be most useful in teaching the individual: a) visual scanning techniques to "look around" the scotoma, and b) the proper defensive survival procedure during the period that vision is impaired.

Still unanswered is the question of visual impairment in critical, time-dependent air or ground maneuvers where weapons must be directed, defensive actions taken, etc. These are the types of situations where visual skills are at a premium. Perhaps as a back-up for the eye protective systems, it would be worthwhile to investigate means by which critical information can be relayed to the operator via a non-visual modality.

X. THE CLASSES OF VARIABLES USED TO ASSESS AND PREDICT THE OPERATIONAL SIGNIFICANCE OF FLASH BLINDNESS AND CHORIORETINAL BURNS FROM NUCLEAR WEAPONS

A. Introduction

There seems to be little controversy among civilian and military operations planners that retinal burns and particularly flash blindness pose a threat to the accomplishment of certain missions.* Two questions which must be answered are: how much of a threat is the visual impairment relative to the other nuclear effects, and what is the exact effect of visual impairment upon mission accomplishment.

At the present state of physiological knowledge, retinal effects and thresholds can be reasonably well described, so it is possible to make rough estimates about safe separation distances. However, the conditions or assumptions used to make such estimates may not be representative of field conditions. There are a host of variables attendant with any field situation which must be considered before making reasonable estimates. Obviously, it is neither practical nor reasonable to include every possible factor in estimating casualties or mission effects. For example, there are fewer variables required to predict ocular effects for a weapon director than for a combat infantryman. The complexity and detail required for a prediction model will vary according to the planner's need for precision or the nature of the specific field situation.

The first major efforts to make assessments of the visual threat were the retinal burn models. Here, weapon and environmental data were manipulated in order to predict retinal exposure. Similar attempts are now being made to develop flash blindness models. Some of these models can be used to compute safe separation distances, on the assumption that weapon and atmospheric parameters can be accurately measured. The

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*As used here, "mission" applies to both military and civilian operations. A civilian mission in time of attack could be the control of an automobile from work to shelter.

input variables for these models, and their interactions, are discussed in earlier sections.

Discussing another set of variables which affect burn or flash blindness probabilities, Whiteside (193) and Neidlinger* consider the probability that the fireball image will occur within the arc of vision subtended by the fovea. Whiteside also mentions that involuntary eye movements may serve to prevent the fireball from focusing on any one portion of the retina; this tending to increase the effective (not theoretical) threshold for burn.

Another class of variables which must be considered in operational threat assessment pertains to the criticality of visual performance during various mission phases. The loss of aircraft control during a period of visual impairment is of great concern. Several investigators have addressed this problem of estimating maximum allowable time for visual decrement during landing, climb-out, weapon delivery, etc. Included in this category is work by Chisum and Hill (28a, 94), Parker et al.(151), and research being conducted at the USAF School of Aerospace Medicine under the direction of Alder.

The next step in the study of visual requirements during mission phases is the reverse of that described above; namely a definition of the minimum vision required during these operations and maneuvers.

The material that follows includes an outline and brief description of 4 major classes of information which would affect the severity, probability, and significance of visual impairment due to burns or flash blindness. While no single model would include each of the following variables, it is intended that the outline will show the complexity of the visual threat from an operations planning standpoint.

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*A research proposal prepared by Major Robert W. Neidlinger, MC, USA. Title: "Retinal Factors in the Production of Mass Casualties", Sub-title, "An Experiment to Demonstrate the Magnitude of the Effect of Retinal Reactivity in the Production of Chorioretinal Thermal Injury".

Wray (197) groups his model information into three classes: energy production, transmission, and ocular absorption effects. For organization of major variables to perform "field" assessments, a fourth category, operational variables, should be added.

B. Variables Associated with Energy Production

1. Weapon Construction

The size (yield), efficiency, and construction method of the weapon will affect the size, pulse rise time and duration, and spectral characteristics of the fire-ball. It is important in interpreting weapon test data that the actual measured yield be used rather than the predicted yield.

2. Detonation Condition

For detonations on or above the earth's surface, detonation altitude has a significant effect upon pulse characteristics, fireball size, and apparent surface temperature. These differences in pulse characteristics as a function of altitude are less pronounced for lower atmosphere bursts than those differences between a low altitude and upper atmospheric detonation.

C. Variables Associated with Energy Transmission

1. Energy Transmission

The character of the atmosphere between the observer and the fireball may have a tremendous influence on the absorbed dose. A significant cloud cover between the observer and the source could attenuate the direct energy by 90 percent or more. While atmospheric properties may intervene to decrease the burn hazard, they may increase the flash blindness hazard by diffusing the image to a larger size. Smoke and aerosols in the atmosphere will increase attenuation. In making casualty or thermal effects estimates, atmospheric attenuation is a significant variable whose effect is often underestimated.

2. Intervening Objects

An object may be located between the source and the observer such that the fireball image is reflected, diffused, or absorbed. Reflecting surfaces causing specular or diffuse reflections can add significantly to the flash blindness hazard. By contrast, anatomical features such as the bridge of the nose or eyebrows may restrict view of the image. Similarly, any non-transparent object which occludes the fireball image from the field of view decreases the threat.

3. Energy Attenuation and Scattering in Ocular Media

Transmission properties of the eye vary as a function of age and condition of the eye. The opacity of the ocular media increases with age, as well as an increase in the amount of scatter. Inasmuch as the majority of the personnel performing critical visual tasks in wartime have essentially "normal" ocular media, this variable is probably not significant.

D. Variables Associated with Absorption of Energy on the Retina

1. Absorption on the Retina

This has been covered in detail earlier in the report, but the variables include:

(a) image size,
(b) spectral characteristics of the radiant energy,
(c) intensity of image irradiance,
(d) pulse characteristics (time duration of source),
(e) amount of energy deposited at any single location on the retina (the retina may move during exposure),
(f) pupil size--static and dynamic,
(g) focus of image,
(h) pigmentation of retinal target area,
(i) histological structure of retinal target area,

(j) thermodynamic properties of target area,

(k) physiological condition of target tissues and cells (age, health, physiological state),

(l) influence of drugs on pupil, lens, and target tissues.

The above three classes are basically theoretical variables, when placed in context of actual field conditions. For example, an individual can be located 100 miles from a high altitude, high yield multi-megaton burst, with optimal atmospheric transmission conditions. But if this individual chances to be "looking the other way" for any number of reasons, no fireball energy will enter the eye. In other words, the theoretical conditions may be ideal for calculation of the receipt of fireball energy, but the probability of this occurrence in an operational setting is subject to the following variables.

E. Variables Associated with the Operational Setting

1. Behavioral/Reflex Responses Affecting Image on the Retina

(a) pupil behavior

(b) pupil size

(c) blink time

(d) blink pattern (close and re-open)

(e) voluntary eye movements at time of flash

(f) involuntary eye movements

(g) orienting and reflex behavior toward a novel visual stimulus. This is determined by:

(1) size, duration, intensity of stimulus,

(2) position of head and eyes relative to source location,

(3) conditioning or training of subject,

(4) state of adaptation,

(5) contrast of source relative to visual field,

(6) degree of visual task occupation at the time of stimulus appearance,

(7) sensitivity and angle of peripheral vision.

2. Effect of Energy Absorption on Visual Performance

(a) location of energy deposition (fovea, parafovea, optic disc),

(b) nature of effect:

(1) permanent:

i. size of lesion or scotoma

ii. depth of lesion

iii. secondary effects such as hemorrhage or ejection of particles into ocular media

iv. physiological response to injury (degree of edema, etc.)

v. healing time.

(2) temporary:

i. duration of afterimage

ii. size of afterimage

iii. location of afterimage

iv. decay characteristics of the afterimage

v. physiological condition of retina (regenerative capabilities of the visual pigments).

3. Effect of Visual Impairment on Task Performance

This is a class of information which is essential in making an operational threat assessment of flash and burns. The basic question is: can the individual "see through" the impairment. This depends upon the degree and type of impairment and the quality and nature of the object to be viewed, as:

(a) intensity, color, size, form, contrast, motion, and pattern characteristics of the visual target object,

(b) quality of vision required to obtain essential information from the object,

(c) maximum time allowed to obtain information (as a function of mission demands),

4. <u>Factors Affecting the Number of Persons Likely to be Exposed to the Fireball</u>

For casualty estimates, military or civilian, there are several factors which would maximize or minimize the exposure probability. Some of these have more influence on the civilian population than the military:

(a) season, as for example vacation time when more people may be out-of-doors,

(b) time of day,

(c) day of the week (a work day versus a week end),

(d) geographical location (a vacation area versus a cold locale where fewer people would be outside),

(e) weather--this not only affects atmospheric transmission, it also affects the number of people likely to be outside,

(f) warning,

(g) occupation.

5. <u>Strategic and Tactical Effects</u>

(a) area over which fireball is visible,

(b) number of persons in the area,

(c) number of persons exposed without protection,

(d) number of persons affected,

(e) of those affected, number that are performing tasks where vision is critical.

6. <u>Factors Which Could Modify or Reduce the Effects</u>

(a) occluding devices

(b) drugs

(c) vehicle control assist devices

(d) training

(e) warning

In summary, the difficulty of making an operational assessment of possible ocular effects depends in some part upon the nature of the individual's task. As mentioned previously, a pilot or weapon director guiding a tactical nuclear weapon by visual means has a very good chance of viewing the detonation. Here, the conditions and effects can be readily predicted to the point of generating firm requirements for protection. However, in cases where the detonation is not expected in time or place, the assessment problem is one of making estimates for the information in Category E, based on experimental and population sampling data.

GLOSSARY OF PHYSICAL UNITS, CONVERSION FACTORS AND STANDARD SYMBOLS

Accommodation - change in refractive power of the eye, expressed as the number of diopters added to the resting refractive power of the eye.

Angle of incidence - angle included between a line connecting the source with a point on a surface and the normal to the surface.

Apostilb - a measure of brightness.

Candle - a measure of intensity of light, the candle used to be the basic unit but has been replaced by the lumen.

Candlepower - a measure of the luminous intensity of a point source been replaced by measures of lumens per steradian.

Emmetropia - ideal condition of the eye, the far point is at infinity.

Footcandle - a measure of illumination.

Footlambert - a measure of brightness.

Illuminance - a measure of luminous flux per unit area.

Irradiance - a measure of luminous flux.

Lambert - a measure of brightness.

Lumen - a measure of luminous flux.

Luminance - a measure of effective brightness.

Lux - a measure of illumination, also called a meter candle.

Millilambert - a measure of brightness, a thousandth of a lambert.

Miosis - constriction of the pupil, may be artificially induced by one percent pilocarpine.

Mydriasis - dilation of the pupil, may be artificially induced by ten percent phenylephrine.

Nit - a measure of brightness.

Photon - a measure of total luminous flux, equivalent to that which passes through a 1 mm^2 pupil when looking at a one lumen source.

Reciprocity - equal total doses (in which exposure time is varied inversely with irradiance) produce identical effects.

Stilb - a measure of brightness.

Solar brightness - the sun at meridian is approximately 519,000 lamberts from the earth's surface. Clear sky is about 2.5 lamberts. The sun at the horizon is about 1885 lamberts.

GLOSSARY (Cont'd.)

Solar constant - 0.135 watts/cm^2 = 0.135 joules/cm^2/sec.

Solar disc - the solar disc subtends an angle of 32 minutes and produces an image of 0.15 mm. diameter on the retina when the lens is focused on the sun. This results in 54 watts/cm^2 through a 3 mm pupil (neglecting loss in the ocular media).

Troland - a measure of total luminous flux passing through a pupil, equivalent to ten times the product of the pupil area (mm^2) and luminance (millilamberts) divided by 3.14.

1 apostilb 0.1 millilambert

1 candle = 1 lumen/steradian

1 candle/cm^2 = 3.142 lambert = 2919 ft. lambert

1 candle lamp = 12.57 lumens lamp

1 footcandle = 1 lumen/ft^2

1 footlambert = 1.076 millilambert = $\frac{1}{\pi}$ candle/ft^2

1 lambert = $\frac{1}{\pi}$ candle/cm^2

1 lumen = 0.00161 watts @ 555 $m\mu$ = 0.000385 gm. cal/sec.

1 lumen/ft^2 = 1 footcandle

1 lux = 1 meter candle = 0.0929 ft. candle

1 millilambert = brightness from 10 lumens/m^2 on a mirror

1 nit = 1 candle/m^2 = $\pi \times 10^{-4}$ lambert

1 stilb = 1 candle/cm^2

The following listing of standard symbols was adopted for use on a Joint Service Project.

Concept	Symbol	Unit	Remarks
Radiant flux	P	cal/sec	Power in the form of electromagnetic radiation
Radiant energy	U	cal	Energy in the form of electromagnetic radiation
Radiant emittance	W	cal/cm^2sec	Radiant flux per unit surface area emitted by a source
Radiant intensity	J	cal/sec steradian	Analogous to candlepower

GLOSSARY (Cont'd.)

Concept	Symbol	Unit	Remarks
Radiance	N	$\frac{cal/sec}{ster\ cm^2}$	Analogous to luminance
Irradiance	H	$cal/cm^2 sec$	Radiant flux per unit area falling on a surface
Retinal irradiance	H_r	$cal/cm^2 sec$	Radiant flux per unit area falling on the retina
Spectral irradiance	$H(\lambda)$	$cal/cm^2 sec\mu$	Radiant flux per unit area per wavelength interval falling on a surface
Retinal spectral irradiance	$H_r(\lambda)$	$cal/cm^2 sec\mu$	Radiant flux per unit area per wavelength interval falling on the retina
Radiant exposure	Q	cal/cm^2	Irradiance integrated with respect to time; that is, the radiant energy which falls per unit area on a surface during a given time interval
Retinal radiant exposure	Q_r	cal/cm^2	Irradiance on the retina integrated with respect to time
Critical energy, or critical radiant exposure	Q_c	cal/cm^2	Radiant exposure required for a given effect on a material sample
Radiant dosage	Q_a	cal/gm	That amount of radiant energy which is absorbed by one gram of material
Spectral reflectance	$r(\lambda), \rho(\lambda)$		The radiant flux reflected from a material surface divided by the incident flux, at each wavelength. "Flux" refers to spatial-total flux. For other conditions, conditions are to be specified.
Spectral transmittance	$\tau(\lambda)$		Analogous to just above, for transmission instead of reflection
Radiant reflectance	r, ρ		$\frac{\int r(\lambda)P(\lambda)d\lambda}{\int P(\lambda)d\lambda}$, where $P(\lambda)$ is incident spectral flux. Value of r depends on source used
Radiant transmittance	τ		Analogous to just above

GLOSSARY (Cont'd.)

Concept	Symbol	Unit	Remarks
Radiant absorptance	A		Unity - τ - r
Spectral emissivity	$e(\lambda)$		$\frac{W(\lambda)}{W_{BB}(\lambda)}$, where W_{BB} refers to a black body
Total emissivity	e		$\frac{\int W(\lambda)d\lambda}{\int W_{BB}(\lambda)d\lambda}$
Luminance	L	cd/m^2	$L = K\int_{380}^{760} N(\lambda)V(\lambda)d\lambda$
Relative luminous efficiency	$V(\lambda)$		Photopic curve for standard eye
Illuminance	E	lm/m^2	$E = K\int_{380}^{760} H(\lambda)V(\lambda)d\lambda$
Retinal illuminance	td	Troland	td = L times area of pupil in mm^2, when L is expressed in Nit (cd/m^2)

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